

Rendezvous and Proximity Operations Handbook

Mission Operations Directorate
Flight Design & Dynamics Division

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Dedication

This book is a monument to the work of Duane Mosel (1940-1986),
"Rendezvouser Supreme," leader/colleague/friend.

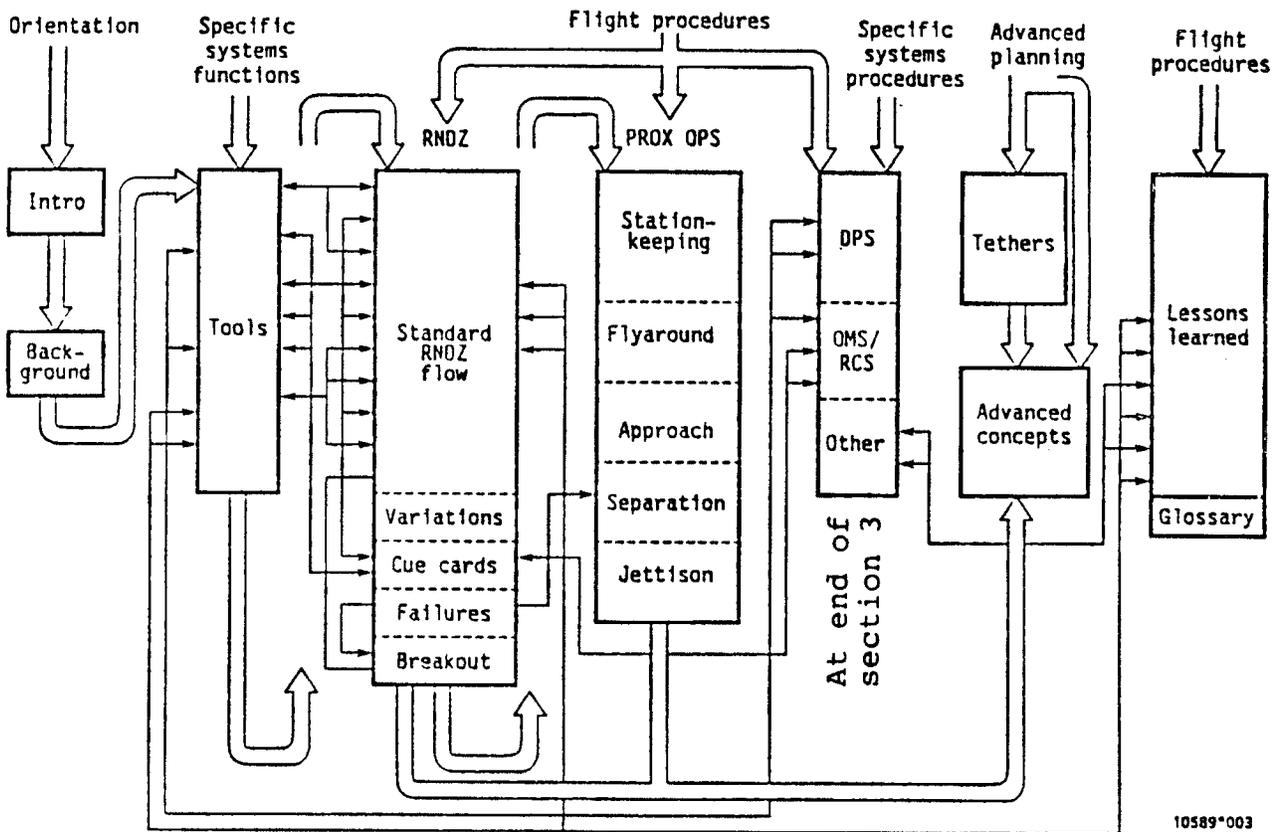
SECTION 1
INTRODUCTION

1.1 PURPOSE

The purpose of the document is to conceptualize the rendezvous (RNDZ) mission phase and to define the techniques and procedures required to perform the Orbiter/target vehicle RNDZ and proximity operations (PROX OPS). The use of this document is to serve as a source of procedures and flight techniques information for flight data file (FDF) development, and to provide rationale and background for all RNDZ operators (flight crew, Mission Control Center (MCC), mission design, payload reps, etc.).

This book represents an attempt to distill and organize the accumulated wisdom of the RNDZ procedures group, the rendezvous analysis groups in navigation (NAV), systems, guidance, flight dynamics, pointing, and other specialists, along with the experience accumulated by flight crews in the 1983-1985 period.

The various possible user entry points are shown in figure 1-1, along with the logic flow and interrelationships of the different sections.



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Figure 1-1.- Handbook entry points and interrelationships.

1.2 APPROACH

This handbook consists of sections on background principles, on tools and techniques, on actual procedures and rationale, and on considerations relevant to future RNDZ missions. Depending on the needs and background of the user, it can be entered at several points. It can serve as a summary/review, as a reference, as a menu of existing procedures, as a guide for defining novel procedures; above all, it is meant to be useful to the spaceflight operations community as a whole.

1.3 STS-UNIQUE FEATURES

Significant changes in vehicle systems and RNDZ mission design have occurred since the RNDZ missions during Gemini, Apollo, and Skylab (1965-1975). These changes required a deliberate and careful reappraisal of all phases of orbital RNDZ as the Space Transportation System (STS) accomplishes it. Some of these changes are:

- A. Targets (TGT's) no longer have transponders, which used to allow ranging at 300 n. mi. The passive "skin track" radar mode only acquires at a range of 10 to 15 n. mi. No target-mounted transponders are currently manifested.
- B. The variety of potential RNDZ TGT's and mission scenarios has greatly expanded. For example, the STS is the first NASA program capable of rendezvous with debris.
- C. Optical sighting techniques have changed. Rather than direct crew sighting through a wide-angle optical system, an automatic star tracker (ST) is provided - but this requires accurate Orbiter pointing to work. Manual pointing is possible through the crewman optical alignment sight (COAS).
- D. The arrangement of the Orbiter reaction control system (RCS) thrusters was dictated by aerodynamic concerns (Apollo command service module (CSM) RCS quads were aligned purely on a geometric basis) which results in significant axis cross-coupling and unwanted translation effects from attitude maneuvers (MNVR's) (the verniers are worse offenders than the primaries). This impacts accuracy of state vector (SV) propagation and of crew control during PROX OPS.
- E. The ground tracking coverage has changed. There is going to be voice and telemetry (TM) contact throughout most of the orbit via the Tracking and Data Relay Satellite System (TDRSS). Tracking coverage for ground navigation is a mixture of three different systems: the S-band Doppler sites of the Ground Spacecraft Tracking and Data Network (GSTDN), the C-band skin-track sites of the Department of Defense (DoD), and Tracking and Data Relay Satellite (TDRS). For secure missions, the GSTDN is replaced by the DoD's Remote Tracking Station (RTS) S-band sites.

F. Although redundancy exists in Orbiter systems such as data processing system (DPS), inertial measurement units (IMU's), etc., many RNDZ NAV sensors are single string.

1.4 REFERENCES

Attitude and Pointing Flight Procedures Handbook (January 1982)
 Vol XIV Payload Accommodations Document (JSC 07700)
 RNDZ 2102 Rendezvous/Proximity Operations Workbook
 Rendezvous Navigation Sensor Characteristics Review, MPAD, February 1985,
 JSC-20355.

1.5 ABBREVIATIONS/ACRONYMS

A/G	air to ground
ACQ	acquisition
ACS	attitude control system
ADI	attitude direction indicator
AIF	auto/inhibit/force switch (SPEC 33)
AOS	acquisition of signal
APU	auxiliary power unit
ARCS	aft RCS
ATT DB	attitude deadband
AUTO	automatic
AVG G	average G (acceleration)
AZ	azimuth to target
AZ-DOT (AZ)	azimuth rate
BODY VECT	body vector
BOS	bright object sensor (star tracker)
bp	barber pole (on a talkback)
CB	constant bandwidth
CCTV	closed circuit television
CCW	counterclockwise
CDR	commander (crewmember)
c.g.	center of gravity
c.m.	center of mass
CMD	command
CNCL	cancel
COAS	crewman optical alignment sight
COMM	communication
CR	change request
CRT	cathode ray tube
CSM	command service module
CW	clockwise
C-W	Clohessy-Wiltshire
CUR	current telemetry vector

D	dimension, as in "two-D meter"
DAP	digital autopilot
DB	deadband
deg/s	degrees per second
DH	differential height
D/N	day/night
DELTA-V	delta velocity
DoD	Department of Defense
dps	degrees per second
DPS	data processing system
DR	discrepancy report
ΔH	delta height between target orbit and chaser
ΔV	delta velocity
ΔT	delta time
DTO	detailed test objective
EE	end effector (of RMS)
EL	elevation of target
EL-DOT ($\dot{E}L$)	elevation rate
ET	elapsed time (also PET)
EVA	extravehicular activity
EXEC	execute
FD	flight day
FDF	flight data file
FDIR	fault detection, identification, and reconfiguration
FDO	flight dynamics officer
FLTR	filtered (SV)
FOD	Flight Operations Directorate (now MOD)
FOV	field of view
fps	feet per second
FRCS	forward RCS
FSL	Flight Simulation Laboratory
FSW	flight software
ft	feet
ft/s	foot per second
fwd	forward
g	acceleration due to gravity
G&C	guidance and control
GCIL	ground control interface logic
GG	gravity gradient stabilization
GNC	guidance, navigation, and control
GPC	general purpose computer
GPS	general processing subsystem global positioning system
H	orbital height (above surface)
H-BAR	angular momentum vector
HST	Hubble Space Telescope

IAH	inertial attitude hold
I'CONNECT	OMS-to-RCS interconnect
I-load	initial load (software)
IMU	inertial measurement unit
INRTL	inertial
IRT	integrated rendezvous target
ISF	Industrial Space Facility
kft	kilofeet (1000 feet)
KITE	kinetic isolation tether experiment
K-load	constant FSW I-load
LDEF	Long Duration Exposure Facility
LED	light emitting diode
LEO	low Earth orbit
LOS	line of sight
LOSA	line-of-sight angle
LRU	line replaceable unit; i.e., any "black box"
LVLH	local vertical/local horizontal
MC	midcourse correction maneuver
MCC	Mission Control Center (Houston)
MECO	main engine cutoff
MET	mission elapsed time
MM	major mode, software
MMU	Manned Maneuvering Unit
MMU	mass memory unit
MNVR	maneuver
MOD	Mission Operations Directorate (formerly FOD)
MPAD	Mission Planning and Analysis Division
mr	milliradian
MS	mission specialist (crewmember)
mV	stellar magnitude
n. mi.	nautical miles
NAV	navigation
NC	phasing maneuver ("C" for "catch-up")
NCC	corrective combination maneuver
NH	height maneuver
NLOS	normal to line-of-sight
NPC	plane change maneuver
NSR	rendezvous coelliptic maneuver
NSTS	National Space Transportation System (office)
OH	overhead
OI	operational increment (flight software release)
OMS	orbital maneuvering system
OMV	orbital maneuver vehicle
OOP	out of plane
OPS	operational sequence, software

OPS-0	idle mode
ORB	orbital
OTV	orbital transfer vehicle
PAD	preliminary advisory data
PAM	Payload Assist Module
pb	pushbutton
PDP	Plasma Diagnostic Package
PDRS	payload deployment and retrieval system
PET	phase elapsed time
PI	plume impingement
PIR	problem incident report (now called DR)
PL	payload
PLB	payload bay
PLBD	payload bay doors
PLT	pilot (crewmember)
PMG	plasma motor generator
PNL	panel
POCC	Payload Operations Control Center
POP	perpendicular to orbital plane
PRCS	primary RCS
PREL	preliminary
PROX OPS	proximity operations phase
PS	payload specialist
PTC	passive thermal control
R	range to target
R-BAR (\bar{R})	radius vector axis
R-DOT (\dot{R})	range rate to target, (+) opening, (-) closing
RCS	radar cross section
RCS	reaction control system
RED	radar enhancement device
REL	relative
REL	release (flight software)
REV	revolution about Earth, usually about 90 minutes in LEO
rf	radio frequency
RFPHB	Rendezvous Flight Procedures Handbook
RHC	rotational hand controller
RM	redundancy management
RMS	Remote Manipulator System
RNDZ	rendezvous
ROT	rotation
rpm	revolutions per minute
RPY	roll-pitch-yaw
RR	rendezvous radar
RSS	"root of sum of squares"
sec	seconds
SEDS	small expendable deployment system
SEP	separation
SES	Shuttle Engineering Simulator
SK	stationkeeping

SM	systems management
SMM	Solar Maximum Mission Satellite
SMRM	Solar Max rescue mission (STS 41-C)
SMS	Shuttle mission simulator
SOR	stable orbit rendezvous
SPARTAN	Shuttle Pointed Autonomous Research Tool for Astronomy (a retrievable free-flier)
SPAS	Shuttle pallet satellite
SPEC	specialist display, flight software
SQRT	square root
SR	sunrise
SRM	solid rocket motor
SS	sunset Space Station
STDN	Spaceflight Tracking and Data Network
STRK	Star trackers (preferred)
STS	Space Transportation System
SUM	summary
SV	state vector
SYS	system
t	time
tb	talkback
TBD	to be determined
TBS	to be supplied
TDRS	Tracking and Data Relay Satellite
TM	telemetry
TF	terminal phase final
TGT	target
THC	translation hand controller
THETA (Θ)	elevation angle of target from Orbiter (local horizontal)
TI	transition initiate maneuver (former acronym for Ti)
Ti	transition initiate maneuver
TIG	time of ignition
TPS	Thermal Protection System
TRK	tracking
TS	target suppress (feature of star tracker)
TSS	tethered satellite system
TSS-D	TSS deployer mechanism
TSS-S	TSS satellite
TVC	thrust vector control
TVR	thrust vector roll
TWT	traveling wave tube (in K-band RR)
UNIV PTG	universal pointing
UP	universal pointing
UPP	user parameter processing (in GPC's)
V	velocity
V-BAR (\bar{V})	velocity vector axis
VEL	velocity
VERN	vernier

VGO	velocity to go
VRCS	vernier RCS
VV	velocity vector
X	cross, as in "X-hair"
XLV	X local vertical
Y	Orbiter/target out-of-plane distance (kft)
Y-DOT	Orbiter/target out-of-plane rate (fps)
YLV	Y local vertical
ZLV	Z local vertical

SECTION 2
BACKGROUND INFORMATION

2.1 DEFINITION

A RNDZ, simply stated, is accomplished when two spacecraft, each in its own orbit, are brought together by a series of systematic and separate MNVR's designed to achieve a gentle meeting at a particular point in an orbit.

One of the two spacecraft is termed the target vehicle and is usually above and ahead of the second spacecraft, which is normally called the chaser. Traditionally the TGT vehicle has been launched first into an unchanging orbit; then, RNDZ MNVR's are performed by the chaser vehicle. The launch windows for the chaser vehicle are normally established so the orbital insertion of the chaser is in the plane of the TGT vehicle, with allowance for differential nodal regression due to initial altitude differences. Once the orbits are coplanar, that is, having a wedge angle between them of 0° , the RNDZ problem becomes two dimensional (altitude and downrange).

After orbit insertion, an orbit adjustment is made to affect the in-plane phase angle between the two vehicles. The RNDZ profile is designed to accommodate a wide range of phase angles at the in-plane launch point. From orbital mechanics it is known that the angular rate of the chaser vehicle, which is launched into a lower orbit, is greater than that of the higher orbiting TGT vehicle. Thus, the chaser will begin to catch up and the phase angle will decrease. The exact catch-up rate depends on the size of the relative orbits.

The chaser vehicle executes orbit shaping MNVR's, based on NAV data from ground sensors and from a succession of on-board sensors. The final MNVR segment of this sequence causes the trajectory of the chaser vehicle to intercept the trajectory of the TGT vehicle. Several small MNVR's are usually planned after this intercept MNVR to assure the chaser remains on an intercept trajectory.

Once close to the TGT vehicle a series of braking MNVR's are performed to prevent the chaser vehicle from flying by, or into, the TGT. Depending on the type of TGT, these MNVR's may be done in close or out at some greater range. Following the braking MNVR's, a stable condition relative to the TGT vehicle (known as stationkeeping) is achieved. At this point, the RNDZ phase is concluded and any further adjustments to the relative positions of the two vehicles fall under the title PROX OPS phase.

PROX OPS can be defined intuitively as the operation of one orbiting spacecraft in the vicinity of another. In more practical terms, it can be defined as a mission phase during which various dynamic trajectory management tasks are conducted manually by one of two coordinating satellites while in the near vicinity of the other. More specifically the relative position and rates are sufficiently stabilized and small (usually

< 0.5 n. mi. and 1 ft/s) so as to preclude the requirement for rendezvous (with all attendant navigation, targeting, and MNVR execution) in order to restore proximity.

PROX OPS includes the traditional functions of stationkeeping, transition (flyaround), approach, and separation. But new functions have been added, ranging from inspection, grappling, or Manned Maneuvering Unit (MMU) operations and retrieval, to various novel medium- and long-range stationkeeping techniques required by STS payloads. Additionally, concerns related to hardware (such as sensor performance, or RCS jet plume impingement), software, and crew procedures are much more important with the STS than previously with Apollo.

This section has presented a simplified explanation. The task of RNDZ and stationkeeping with another orbiting vehicle can become quite complicated. For this reason a standardized set of systematic MNVR's is designed to accomplish the following:

- Maximize the probability of success.
- Achieve the RNDZ at a particular point in the orbit (dictated primarily by lighting conditions) with a single fixed crew timeline, generated a year before the flight.
- Accommodate all potential phasing conditions and requirements
- Optimize the use of crew time in orbit
- Minimize the amount of propellant used
- Optimize the use of onboard NAV sensor capabilities

These tasks break down into five basic components, each of which is to be addressed in detail in this handbook. They are:

- Vehicle control
- NAV
- Targeting
- MNVR guidance
- Terminal phase manual trajectory control (including braking operations)
- PROX OPS

Different techniques are used to "control" the Orbiter trajectory during RNDZ and PROX OPS. RNDZ operations utilize closed loop guidance, navigation, and control to achieve a desired relative state. PROX OPS utilize crew visual observations and piloting techniques (along with universal pointing (UP) attitude control) to achieve a desired relative state.

Navigation starts with ground tracking of both vehicles. When the relative range decreases to several hundred miles, onboard relative NAV can be used. Relative NAV involves the manner in which the various tracking sensors (radar, STRK, and COAS) are operated with the goal of improving the accuracy of the onboard relative state. After sufficient NAV data have been processed, the crew targets the required velocity correction for the subsequent RNDZ MNVR. This involves computation of a solution using the targeting equations. After maneuvering to the burn attitude and making the other necessary preparations, the crew initiates the MNVR at time of ignition (TIG). RCS burns are executed manually with the translational hand controller (THC). However, orbital maneuvering system (OMS) burn execution is more automatic and only requires the crew to monitor the system and guidance parameters on the cathode ray tube (CRT) display (and push the execute key prior to TIG). Upon MNVR completion, the cycle repeats itself with additional relative NAV. After the final post-Ti midcourse MNVR, the crew can manually achieve stationkeeping by:

- Translating normal to the line of sight (LOS) to maintain an intercept trajectory
- Translating (braking) along the LOS to achieve a velocity match

Other tasks which are not unique to RNDZ operations, but are performed during this phase, should be noted. These include:

- Ground-targeted OMS burns
- IMU alignments
- Systems management
- Orbiter/MCC communications interface

Therefore, to ensure accurate NAV it is necessary to minimize IMU drift, and an alignment is scheduled at the beginning and end of each day, and prior to the rendezvous phase. Systems management is the ongoing function of monitoring the non-guidance, navigation, and control(GNC)-related systems. Communications between the MCC and the crew include uplinks (SV's, accelerometer bias, gyro compensation), MCC MNVR voice pads, and burn status reports.

2.2 CREW ASSIGNMENTS

Three crewmembers are normally sufficient to perform a RNDZ. Exact allocation of crewmembers and of functions may be at the discretion of the commander (CDR), but the following guidelines reflect experience and analysis. Assignments of the previously defined tasks to the RNDZ crewmembers are based primarily on the crewmember's major areas of responsibilities during other mission phases, timeline division of duties, and their location in the crew station.

One crewmember would assume the major responsibility for the flight control system, which involves the targeting and execution of all translation and attitude maneuvers (RCS and OMS). The duties include maneuver preparation, guidance monitoring, and the execution of the Orbiter MNVR's required during terminal phase braking operations. During periods of low flight control activity, this crewmember handles the communications (COMM) with the MCC, performs guidance, navigation, and control systems monitoring activities, and assists the second RNDZ crewmember as required.

The main responsibility of additional RNDZ crewmembers during the RNDZ phase could be the management of the NAV sensors and software. The first crewmember's assistance, however, may be required for the data taking and computation of any backup MNVR solutions. The IMU alignments are performed by another crewmember as required during the non-NAV periods. Another RNDZ crewmember also performs certain systems monitoring functions with primary responsibility in the area of systems management (SM) related systems.

The division of duties between the RNDZ crewmembers is not exact and will require some overlap when dictated by the timeline.

With RMS operations added in, another crewmember becomes necessary at the aft control station. Flight experience has shown that many extra foot-loop restraints were required (including one on the aft wall so a crewmember could "stand" there to work forward CRT's); further, careful attention is needed to coordinate who goes where, and when.

2.3 REFERENCE SYSTEMS

2.3.1 Relative Motion Plots

The motion of a chaser satellite relative to a TGT satellite (in a nearly circular orbit) can be viewed from several different reference frames. Traditionally, orbits are viewed in a geocentric inertial frame. However, for orbital RNDZ a TGT-centered curvilinear frame rotating at orbital rate (thus maintaining local vertical/local horizontal (LVLH) orientation) is much more convenient in terms of conceptualization. The following paragraphs discuss chaser satellite orbits in both frames.

If the chaser is in a lower, circular orbit (fig. 2-1), its relative motion will be a constant velocity path at a constant ΔH below the TGT. The chaser overtakes and passes the TGT because of its greater orbital velocity. The rule of thumb is: relative horizontal displacement (or downtrack growth rate) is about 10 times the average ΔH per revolution about Earth (REV).

2958. ART. 2

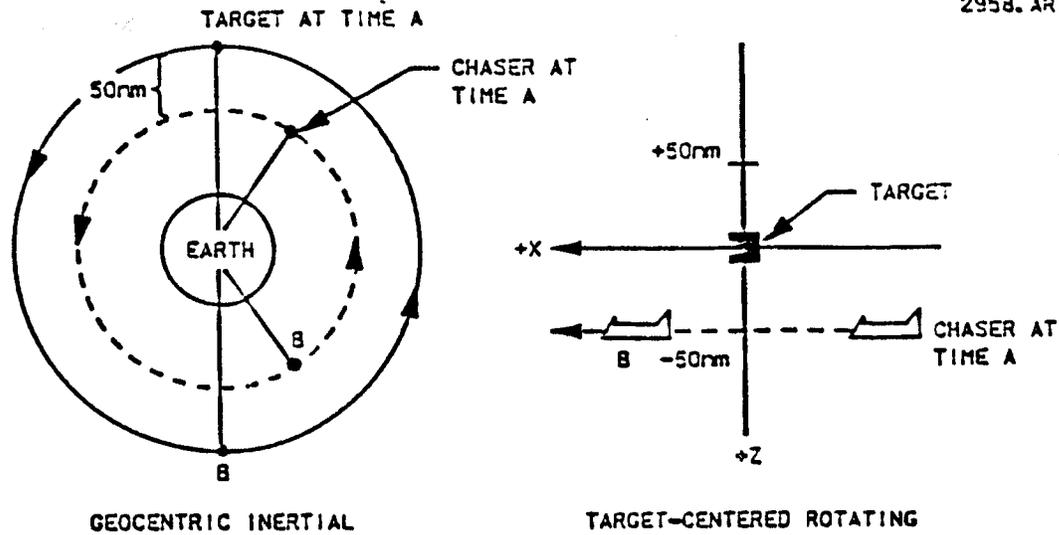
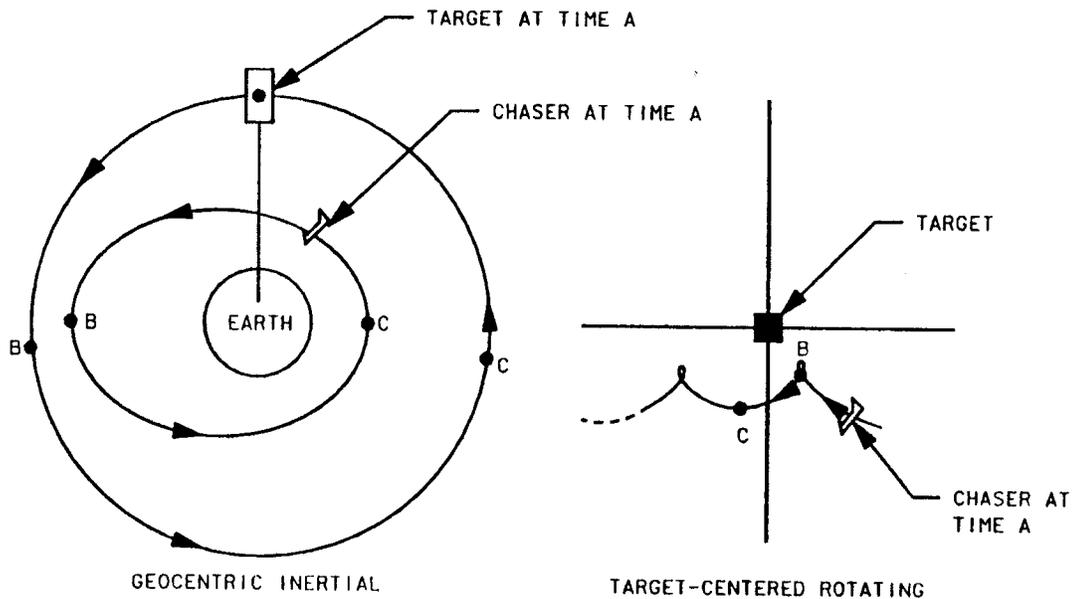


Figure 2-1.- Relative motion plot, circular orbits.

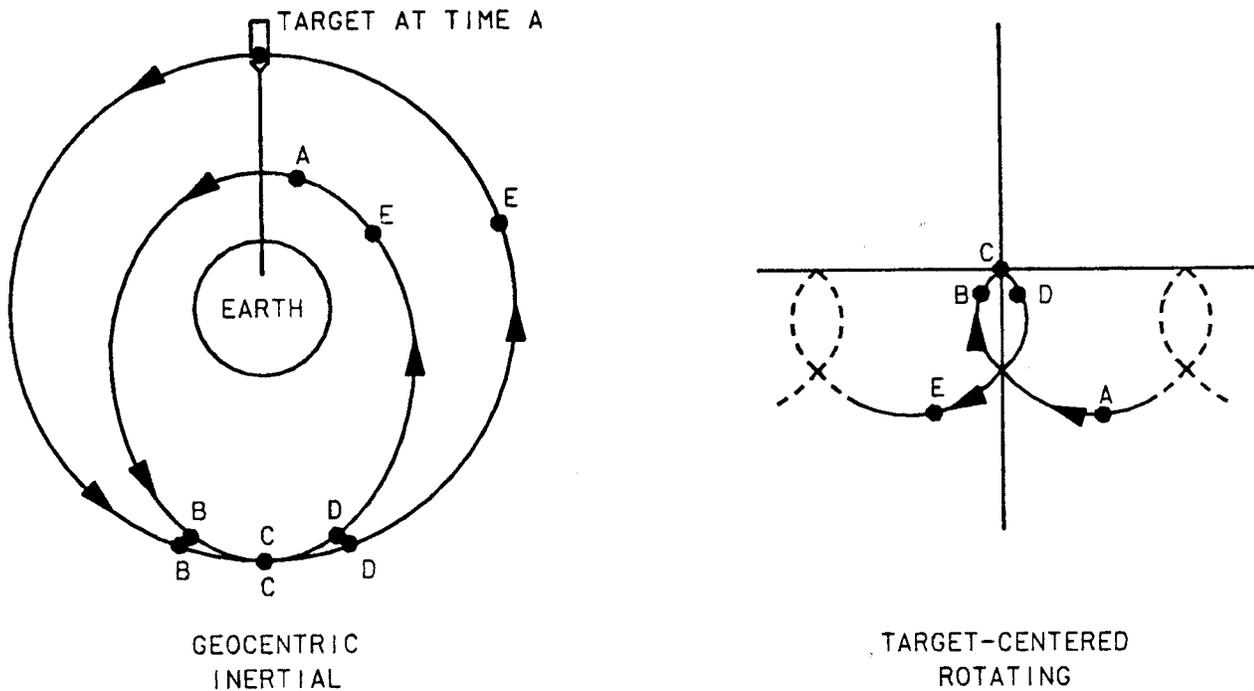
If the chaser is in an elliptical orbit below the TGT (fig. 2-2), it, of course, is going faster at perigee and slower at apogee. Relative to the TGT, the chaser moves more and more slowly the higher it gets, to the point that at chaser apogee the TGT may actually be going faster (this makes the relative motion plot of the chase position appear to double back on itself for a brief interval near apogee, when the TGT is actually outdistancing the chaser).



2957. ART. 5

Figure 2-2.- Relative motion plot, elliptical chaser orbit.

The next step is for the elliptical orbit of the chaser to actually touch the target orbit (fig. 2-3). The final approach trajectory is thus seen to be from below and ahead of the TGT. To match orbits, the chaser must then raise its perigee to the TGT altitude by increasing its velocity (firing in the direction of the flight path).



(TARGET IN CIRCULAR ORBIT)

2956. ART, 5

Figure 2-3.- Tangential orbits.

In practice, final approach trajectories utilize elliptical orbits which cross that of the TGT (fig. 2-4). The chaser makes a final burn at apogee (the T_i burn), so intercept occurs less than 360° later. This results in a "hot" approach in which the chaser closes in on the target stationary against a stellar (inertial) dark background, with a finite range rate at intercept (thus, real-life dispersions will not have as great an effect on the trajectory as they would in the case of a minimum-energy, Hohmann-type transfer.) At this point the crew takes manual control, bleeds down the range rate, and completes the rendezvous.

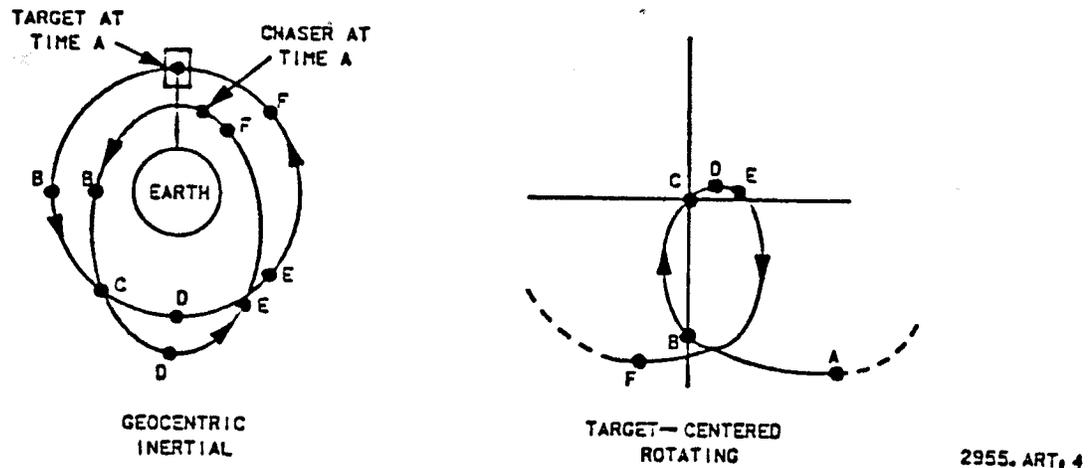


Figure 2-4.- Intersecting orbits.

In figure 2-21, the relative motion plot of a Solar Maximum rescue mission (SMRM)-type RNDZ shows examples of these above types of motion during various mission phases.

2.3.2 Vector Definitions

The V-BAR is along the direction of circular satellite motion, positive ahead. The R-BAR is the direction to the center of the Earth, positive is down. The H-BAR, or angular momentum vector, completes the three dimensional framework and points positive to the left (on posigrade orbits this is north). Alternately, R is down, H is as in classical dynamics, and V completes the orthogonal system. Note that for noncircular orbits, V-BAR only aligns exactly with the dynamical velocity vector at apogee and perigee; otherwise, it can be up to a few tenths of a degree off.

The XYZ coordinate nomenclature is also used for this local vertical frame. X is along the V-BAR, Z is downward along the R-BAR, and Y completes the righthand frame. The UVW framework is local vertical inertial, with $+U = -R$, $V = V\text{-BAR}$, and W completing the frame.

2.4 ORBITAL MECHANICS EFFECTS

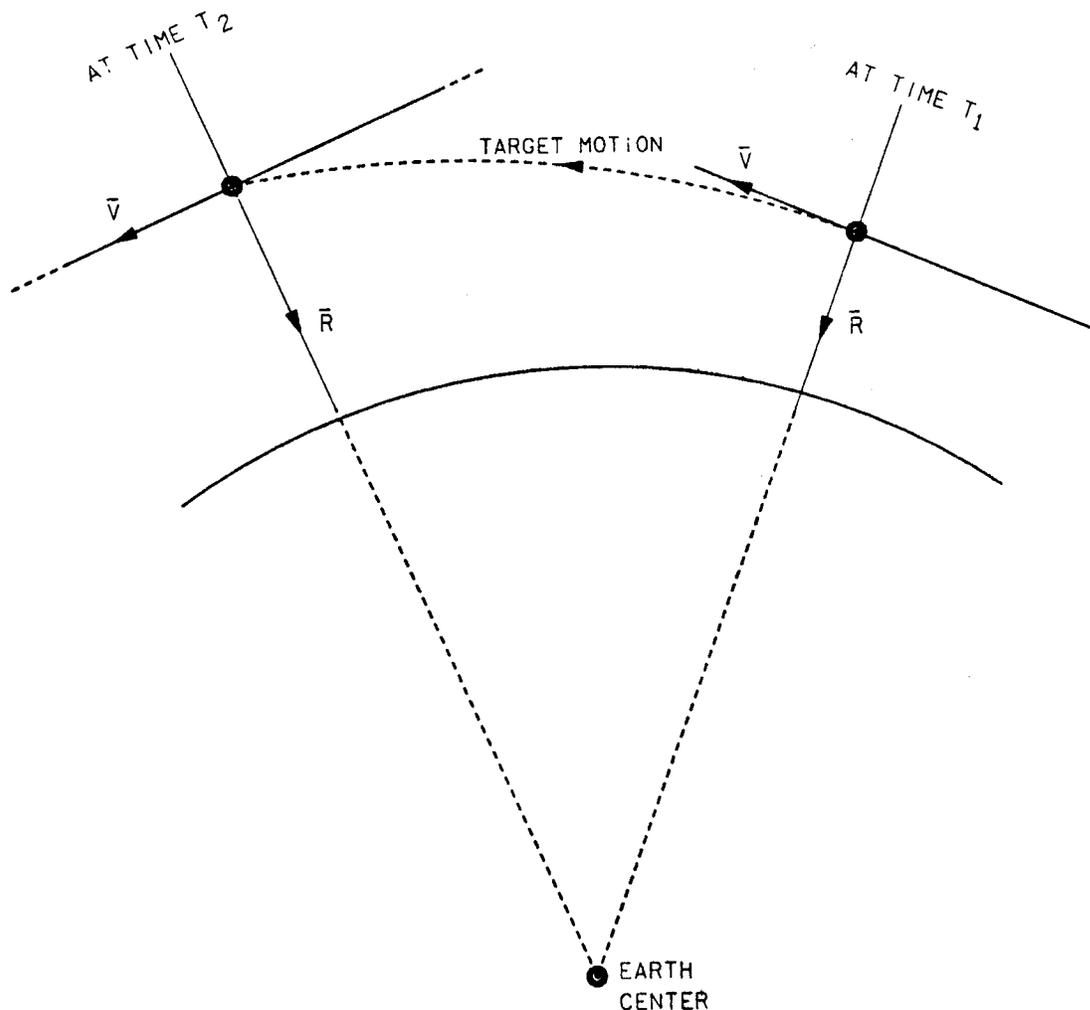
The common-sense approach towards the laws of motion is based on everyday experience combined with familiarity with Newton's Laws concerning action-reaction and $F = MA$, etc. A thrust in a direction will cause motion in that inertial direction, along a straight line and at a speed proportional to the original thrust. Disturbing forces can slow down that motion or shift its direction.

The laws of motion of two independent objects orbiting the Earth in close proximity to each other, however, are not as well grounded in "common

sense". Newton's Laws still apply, of course, but orbital mechanics effects resulting from the inverse square force field often alter the "common sense" results of simple directional thrusting when viewed in the target-centered (non-inertial) rotating frame. Although the resulting relative motion is not necessarily intuitive, it is predictable.

2.4.1 Relative Motion of Two Objects Orbiting in Proximity

This discussion uses a TGT-centered frame of reference, rotating at orbital rate to stay level with the local horizontal plane (fig. 2-5). Imagine two satellites flying formation in approximately circular low-Earth orbit (100-300 n. mi altitude, period about 90 minutes) with parallel velocity vectors in this frame and identical drag characteristics. One is the TGT and the other (usually the Orbiter) is the chaser.



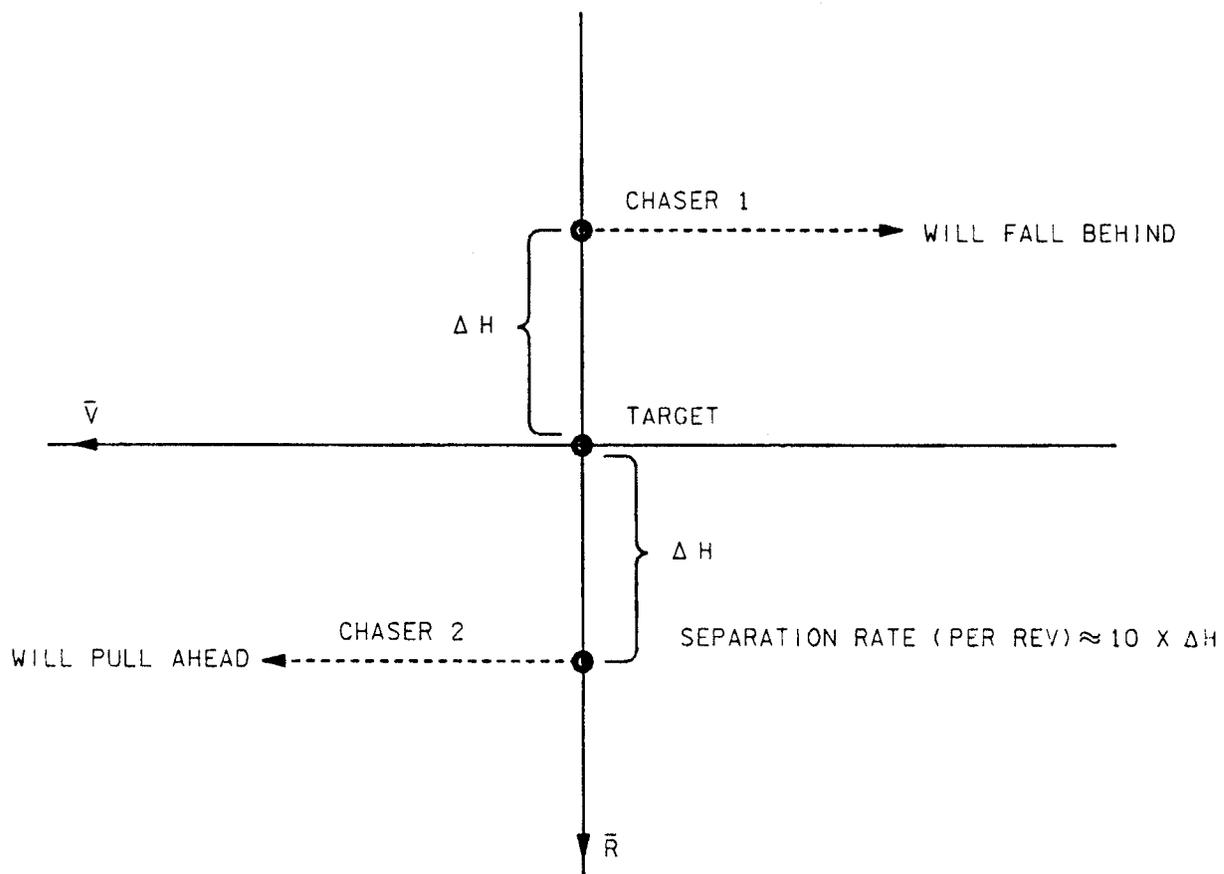
1223, ART, 4

Figure 2-5.- Target-centered frame (rotating at ORB rate).

2.4.1.1 Above/Below (R-BAR (Radial) Displacement)

If the two objects are co-planar and are initially on the same R-BAR (radius vector) at different altitudes and both are in stable circular orbits, they will drift apart at a constant horizontal rate due to the difference in orbital velocities at these different altitudes (fig. 2-6). If the chaser is above the target, it will drift behind; if below, it will pull ahead. A rule of thumb is that this horizontal displacement per REV is approximately ten times the vertical difference (the analytical solution is 3π times the separation).

Two objects are said to be in co-elliptic orbits if the orbits' apsides are aligned and the difference in apogee height is the same as the difference in perigee height. In terms of orbital parameters, $a_e = a_e$.

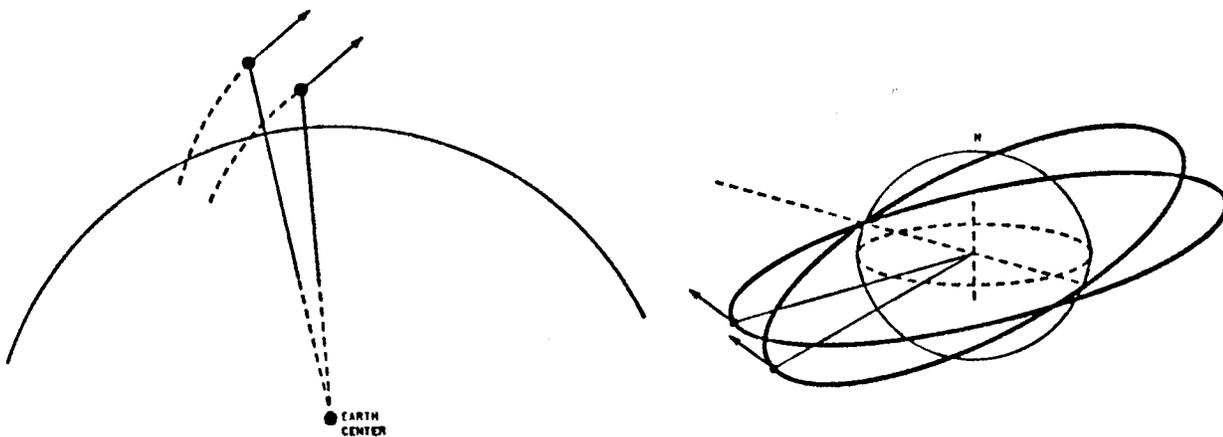


1223. ART, 5

Figure 2-6.- Radial separation relative motion.

2.4.1.2 Lateral (out of plane)

If the two objects are at the same altitude and velocity, but are not coplanar, with their LOS perpendicular to their V-BAR (fig. 2-7), they will cross each other's path twice per orbit in a series of scissors maneuvers (in a sinusoidal fashion). Starting at a given range (the maximum out-of-plane separation), the position of the objects will coincide after a quarter REV (about 22 minutes) and then be at the same distance apart, but on opposite sides after 45 minutes (half a REV). At the completion of one full 90-minute REV they will again be at their original positions with their original relative motion.



1273. ART. 6

(This is not a stable formation!)

Figure 2-7.- Out-of-plane parallel motion (two views at max separation).

2.4.1.3 Ahead/Behind (V-BAR displacement)

If the objects are co-planar and at the same altitude and velocity (fig. 2-8), they will maintain their initial relative displacement and motion. That is, they will be in a stationary relative position.

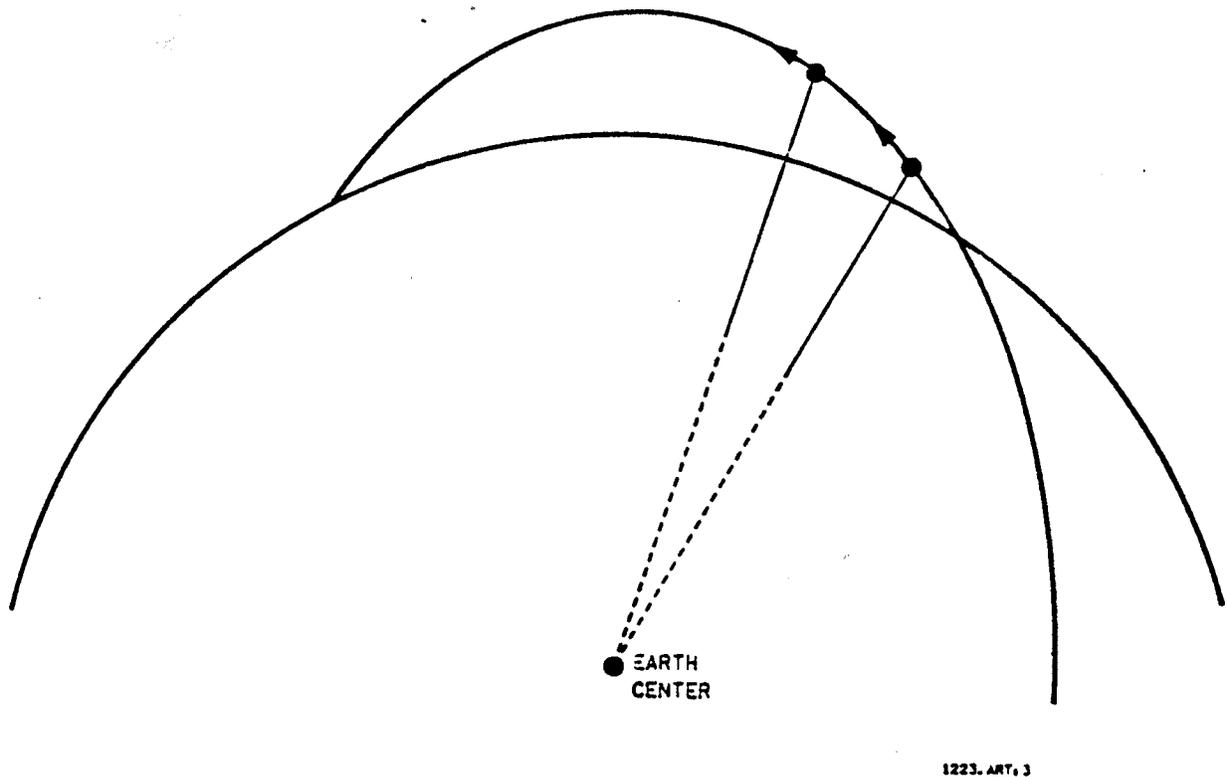


Figure 2-8.- Two satellites on V-BAR.

2.4.2 Effects of Maneuvers from a Stable Relative Position

Imagine the two co-orbiting objects in a stable formation, the chaser ahead (that is, on the +V-BAR) of the TGT. Small ΔV 's by the chaser can have dramatic results. The following examples are based on a 1 ft/s pulse (e.g., a 5-second firing of two RCS jets); different impulse sizes can be scaled linearly within a reasonable range. Altitude differences are reflected in multiple values, one for 150 n. mi. and the other for 250 n. mi.

Note that since small burns perpendicular to the velocity vector do not effectively alter the total velocity (and energy) of the satellite, they do not change its orbital period. Hence, they lead to closed, repeating cycles (with respect to a TGT-centered frame of reference) which return to the same point every REV (it is a "periodic" displacement). In quantitative terms, since the speed of the satellite is about 25,000 ft/s, a perpendicular burn of about 10 ft/s gives a new speed only slightly different from the initial value (actually, 25,000.002 ft/s).

However, burns which are parallel to the velocity vector alter the total energy of the satellite, and in turn cause cumulative relative displacements from the starting point, or "open" curves. This is called a "secular" displacement.

If a burn has components in different directions, the result can be approximated by vector additions of the results of each component.

2.4.2.1 Ahead/Behind (V-BAR Burn)

Thrusting towards the TGT from ahead of it (retrograde thrust) will cause initial movement toward the TGT. However, orbital mechanics effects will then cause the chaser to begin dropping and slowing within 10 minutes (after traveling about 300 feet in the desired direction while dropping the same amount), and then start pulling away from the TGT (fig. 2-9). The same maneuver toward the target, executed from behind the target, will cause the chaser to initially approach, but then gain altitude and start falling behind the TGT. Each REV, the chaser will be about an additional 17,000 feet further away from the target (without orbital mechanics effects, one would expect to move about 5400 feet per REV in a direction toward the TGT). The motion (in the "from behind" case) is due to the fact that the chaser is now in an elliptical orbit approaching apogee, and hence slowing; that orbit has a longer period than the original one, and therefore the chaser arrives back at its starting point somewhat later.

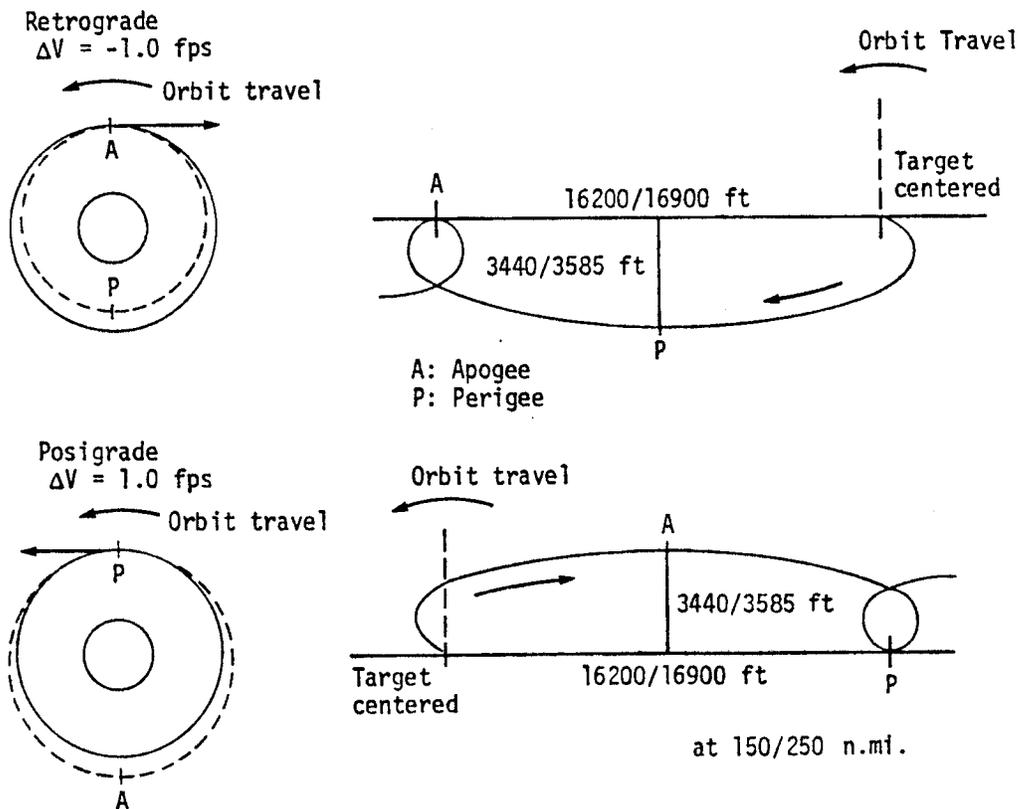


Figure 2-9.- V-BAR burn effects.

2.4.2.2 Out Of Plane

Thrusting horizontally out of plane (OOP) will cause initial motion in the desired direction, but that motion will slow and come to a halt after about 22 minutes (one quarter REV) (fig. 2-10). The chaser will have moved 900 feet off to the side (if there were no orbital mechanics effects, it would have moved 1300 feet and still be moving). The chaser will then swing back towards its initial position and pass through the position (with velocity opposite to the starting value) 45 minutes (half a REV) after the maneuver. The chaser then swings out to the other side the same amount and continues the cycle indefinitely. Deviations in altitude and along V-BAR are negligible. What has happened is that the orbit plane has been slightly tilted (about 450 ft/s is required to tilt the plane 1° , which is equivalent to a max separation of about 60 n. mi).

See section 2.9.2 for OOP control strategy.

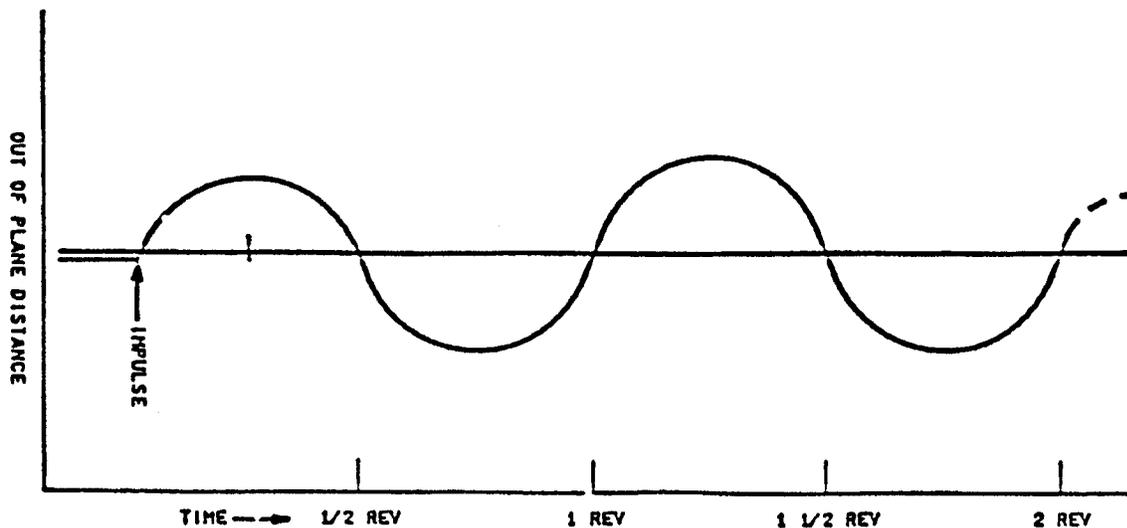


Figure 2-10.- Impulse out of plane.

2.4.2.3 Radial (Up/Down)

Thrusting radially outwards (that is, away from the center of the Earth, or "up") creates an initial vertical motion in the desired direction, but the chaser then begins falling behind its original position while the upwards motion slows and stops (fig. 2-11). A quarter REV (22 minutes) after the impulse, it is about 900 feet higher (it would have been 1300 feet higher and still moving, if it hadn't been for orbital mechanics effects) and about 1700 feet behind its original position, with all motion in the horizontal direction. Drifting downwards as well as backwards, and 45 minutes (half a REV) after maneuver execute, the chaser drops through its original altitude

at a range of about 3500 feet from where it started. It then continues in this "football" trajectory, dropping but moving forward, then rising and resuming its original position after a full orbit. The motion then repeats, subject to outside perturbations.

Thrusting radially inwards (downwards) creates the same-sized "football" orbit which first pulls ahead and then backwards in its 90-minute cycle.

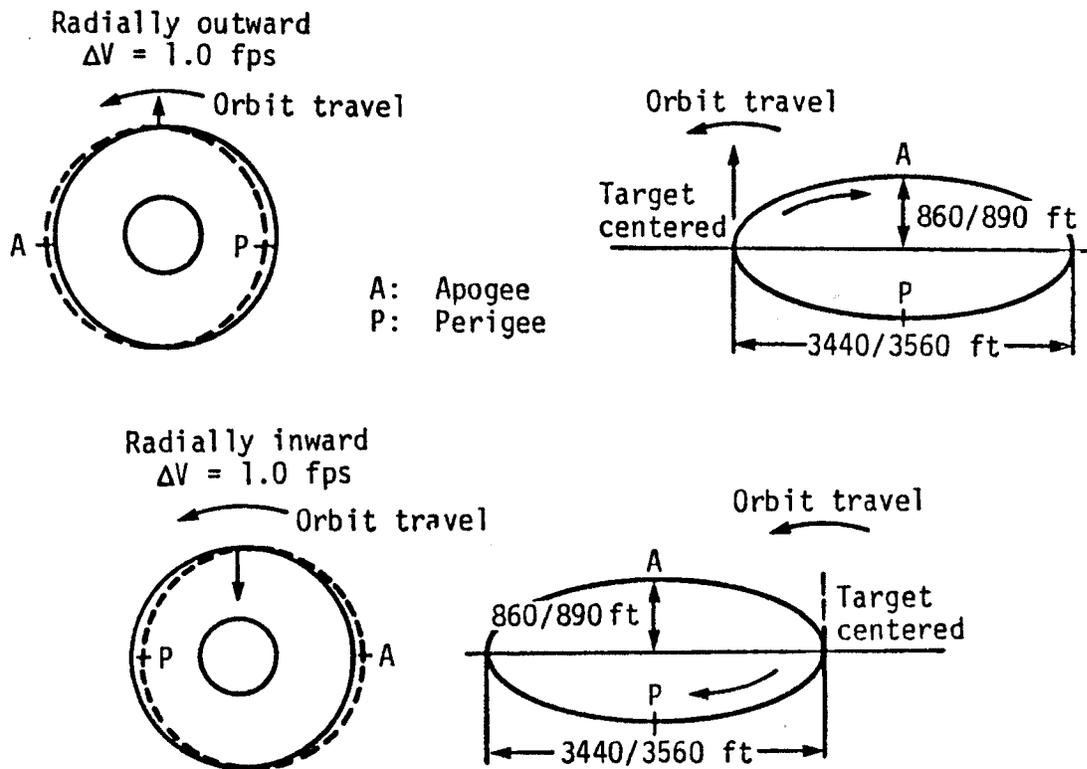


Figure 2-11.- \dot{R} thrusting effects.

2.4.3 Use of Orbital Mechanics

For final approach to a TGT and for subsequent stationkeeping, it may be desirable to minimize RCS plume impingement on the TGT and to minimize forward reaction control system (FRCS) usage. In certain strategies, "orbital mechanics" can be used to obtain braking effects, somewhat like "free" RCS translation impulses. These useful effects are achieved by actual RCS burns which can be designed to be orthogonal (at right angles) to the chaser-target LOS. This avoids plume impingement, and if the burns can be arranged to be +X Orbiter body axis, also avoids substantial FRCS usage. See figure 2-12.

Of the following three techniques (orthogonal braking, R-BAR approach, and V-BAR approach), only the last is normally used in STS operations. The others may have important applications in future operations.

2.4.3.1 Orthogonal Braking

A technique called orthogonal braking uses +X axis braking. In order to reduce the possibility of plume impingement on the TGT, the +X burns are made perpendicular to the LOS to the TGT vehicle. In this technique, orbital mechanics effects, supplemented by the +X jet firings, result in the Orbiter braking with respect to the TGT (fig. 2-12). The braking scheme is accomplished by placing the Orbiter in the TGT track mode, with the -Z axis pointed toward the TGT. Trajectory analysis is done on the ground preflight to determine the targeted points, with a specified time interval between them (5 minutes or so). These positions and times for the braking maneuvers are part of the flight software I-loads. This software is also used to compute the magnitude of the thrust necessary to intercept the specified offset position using only RCS firings perpendicular to the TGT LOS.

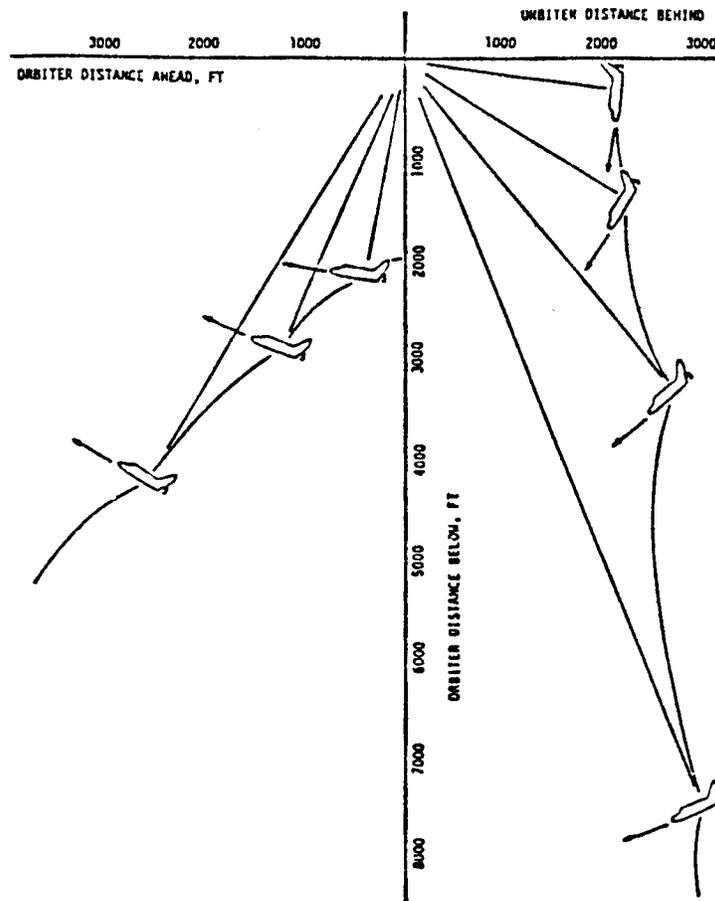


Figure 2-12.- Orthogonal braking.

2.4.3.2 Motion Along Up The R-BAR

Orbital mechanics effects can provide an apparent braking force for an R-BAR approach. This technique minimizes PRCS thrusting toward the TGT (theoretically zero).

The sequence in figure 2-13 illustrates a separation technique. Assume the Orbiter is 1000 feet below the target with zero relative velocity (fig. 2-13-A). If no crew action is taken, the Orbiter will begin moving down and ahead because its orbital velocity is not sufficient to maintain an orbit that is coelliptic (that is, has the same orientation of semi-major axis and has the same ΔH at apogee and perigee) with the TGT (fig. 2-13-B). An LVLH attitude hold mode is used to automatically maintain the Z axis parallel to R-BAR (Orbiter X axis aligned with V-BAR) while the forward firing primary reaction control system (PRCS) thrusters are used to null the forward movement and maintain the Orbiter on R-BAR. The Orbiter accelerates radially downward from the TGT (fig. 2-13-C).

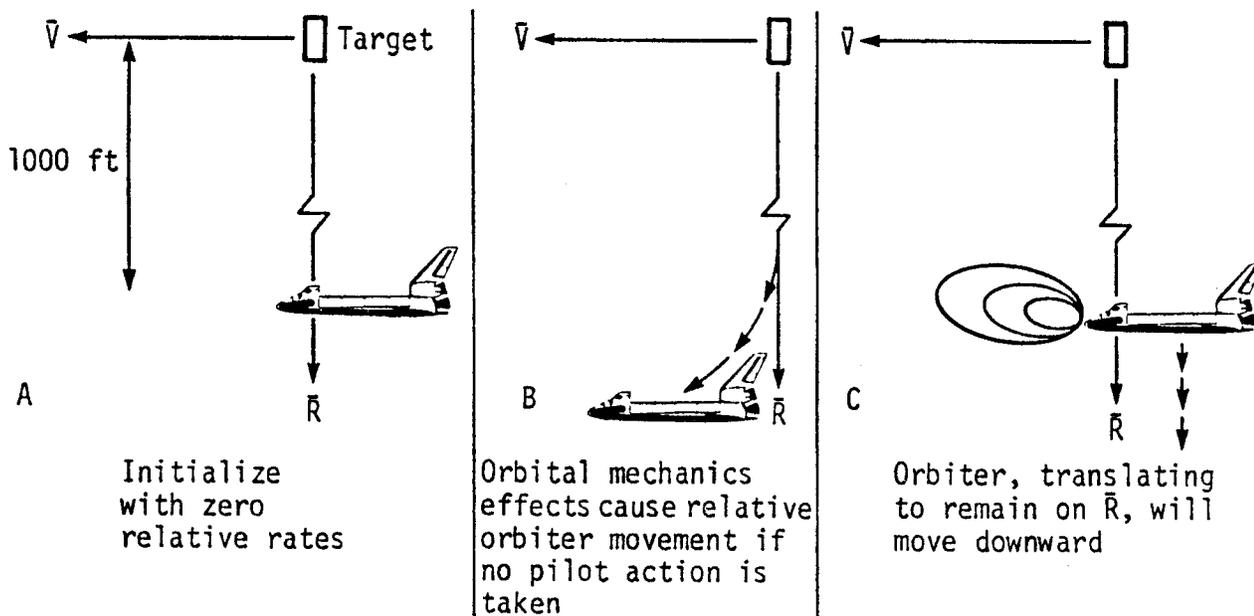


Figure 2-13.- Orbital mechanics effects in separating.

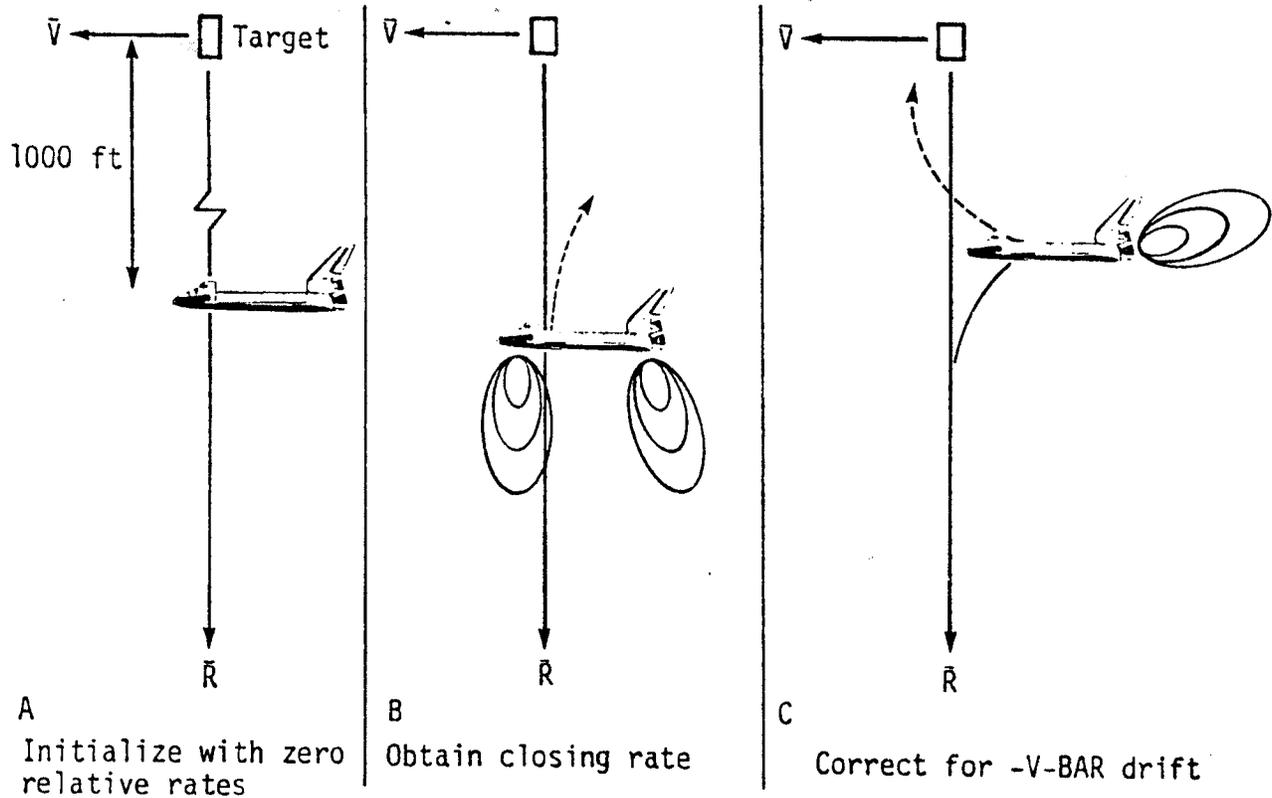


Figure 2-14.- Orbital mechanics effects in braking.

Orbiter approaches to the target can be controlled in a similar manner. As in figure 2-13-A, initialize the Orbiter on the R-BAR but this time with a sufficient closing rate (see fig. 5-20). Orbital mechanics effects will then cause the Orbiter to move up in altitude and drift behind the target (fig. 2-14-B). Then +X body axis burns are used to return to the R-BAR while still rising. The Orbiter then maintains itself essentially on the R-BAR, closing on the target with only subsequent +X burns as needed.

The R-BAR approach can also be considered in terms of the orbital parameters of the two vehicles. The Orbiter is at apogee in an elliptical orbit in figure 2-13-A. As it moves away from apogee, its altitude decreases and its speed increases - hence, in figure 2-13-B, it will pull ahead of, and further below the TGT which is in a circular orbit with constant velocity. Thrusting retrograde (fig. 2-13-C) will provide short-term counteraction to the forward drift, but will make the tendency to drift down even worse. The R-BAR closing approach dynamics are similar.

2.4.3.3 Approach Along The V-BAR

The V-BAR approach is initiated with a THC pulse directed toward the TGT (aft RCS canting adds a component slightly above [below] the local horizontal), if ahead of [behind] the target. If leading the TGT, this

small ΔV component results in a trajectory which rises a small distance above V-BAR before beginning to fall relative to the TGT. This normal ΔV component is obtained from Orbiter translation cross-coupling from a -Z acceleration (toward the TGT) into the +X axis (normal to V-BAR). If no corrections were performed at the V-BAR crossing, the Orbiter would eventually fall below V-BAR and move farther ahead of the TGT (dashed line in fig. 2-15). This is because the ΔV applied was primarily a retrograde burn which lowers the other side of the orbit. The reduced average orbit altitude of the Orbiter causes a difference in orbital rates (i.e., Orbiter traveling faster than target), and the Orbiter moves ahead of the TGT. Therefore, to maintain a closing rate, the crew must thrust up (normal to the TGT LOS) at each V-BAR crossing to produce a series of trajectory hops until the capture distance is achieved. Note that because of RCS cross-coupling, firing the Orbiter +X jets to maintain altitude also slows the closing rate. (The thrusting up has the theoretical effect of reducing the gravitational acceleration on the Orbiter, which allows it to maintain the same altitude as the TGT at a lower velocity, resulting in the Orbiter being overtaken by the target satellite.) To stabilize the Orbiter at a desired range, RCS firings toward the TGT (acceleration away from the target) is required in order to restore full circular orbital velocity to the Orbiter.

2.5 RENDEZVOUS PARAMETERS

Sensors are used by the crew during rendezvous to obtain information about the relative position of the Orbiter with respect to the TGT. This information is then utilized to determine translation corrections which may be needed based on desired position. Some parameters can also be computed by NAV or by manipulation of timed marks of other parameters.

The parameters used are range (R), range rate ("R-DOT"), elevation (EL), azimuth (AZ), pitch inertial angle rate (EL-DOT), and roll inertial angle rate (AZ-DOT).

2.5.1 Range

Ordinarily, R is considered to be the LOS distance between the Orbiter center of mass (c.m.) and the TGT c.m. However, the reference point for the raw data is not really the Orbiter c.m., but is the sensor itself and this is noticeable during PROX OPS. (This offset is accounted for in GN&C FSW for proper navigation.) The rendezvous radar (RR) (see section 3.3.4.2) provides range from the TGT to the Ku-band antenna; the closed circuit television (CCTV) tilt technique (section 3.3.5.3) provides distance from TGT to the Orbiter structure (i.e., "clearance"); the angular size technique (section 3.3.6) provides range to the visual sensor (CCTV or eyeball). There can be both proportional (scale) and constant delta (offset) biases.

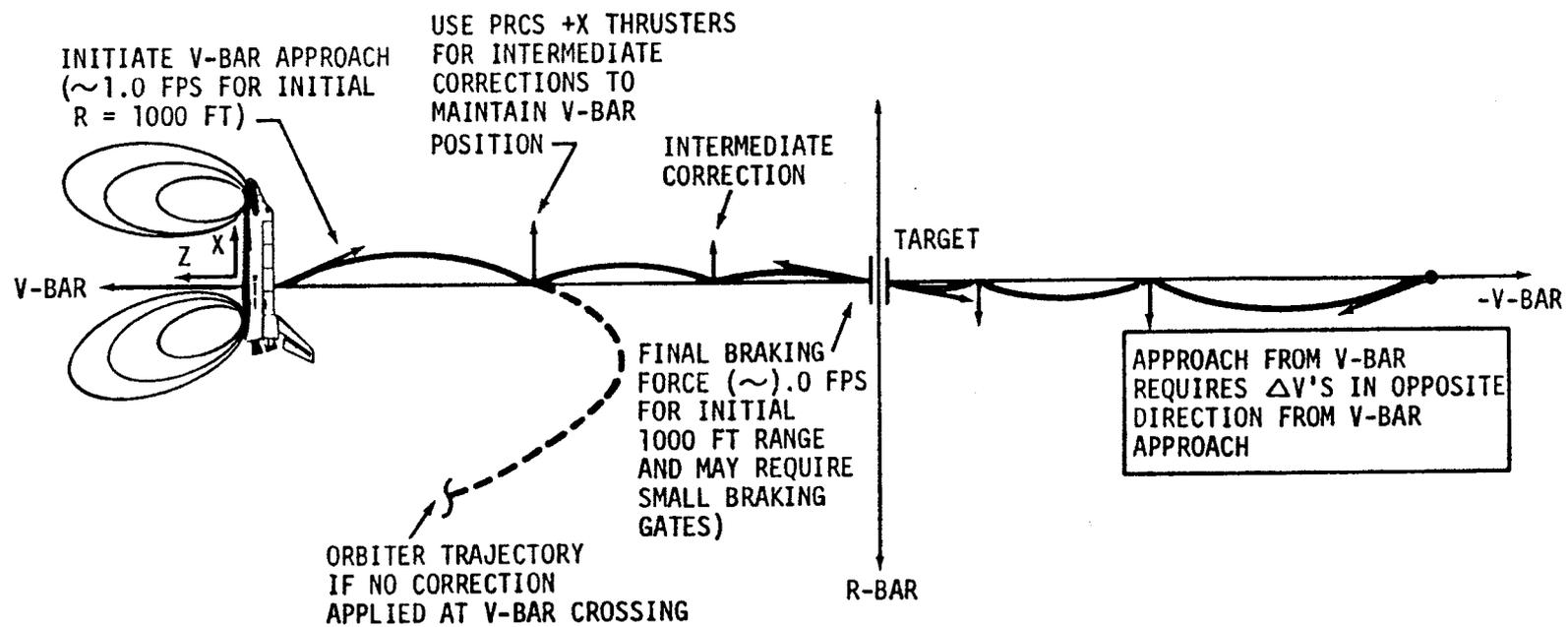


Figure 2-15.- V-BAR approach technique.

2.5.2 Range Rate

R-DOT is the rate at which the range measurement is changing with respect to time; positive is an opening rate, negative is a closing rate. This can be observed directly by a sensor (e.g., RR) or computed using successive range marks.

2.5.3 Elevation

2.5.3.1 Radar Elevation

The RR null position is along the Orbiter -Z axis. The radar EL is then the pitch position of the radar relative to its null position ($\pm 90^\circ$); positive sense - antenna LOS motion toward the Orbiter nose, the +X axis (fig. 2-16).

2.5.3.2 COAS Elevation

COAS elevation is the vertical position (Orbiter X, Z plane), in degrees, of the target position in the COAS field-of-view relative (FOV) to the Orbiter -Z axis. This is assuming the COAS is aligned perfectly with the Orbiter -Z axis. Whenever the Orbiter -Z axis is aligned parallel to the V-BAR, with the Orbiter X axis in the TGT orbital plane, this angle provides an indication of the $\pm X$ axis thrusting required to drive the Orbiter back to the V-BAR. See section 3.3.3 for details.

2.5.3.3 STRK Elevation

See section 3.3.1 for -Z and -Y STRK angles.

2.5.4 Azimuth

2.5.4.1 Radar Azimuth

The AZ is the roll position of the radar relative to its null position ($\pm 180^\circ$); positive sense - antenna LOS motion toward the Orbiter left wing, or -Y axis (fig. 2-16).

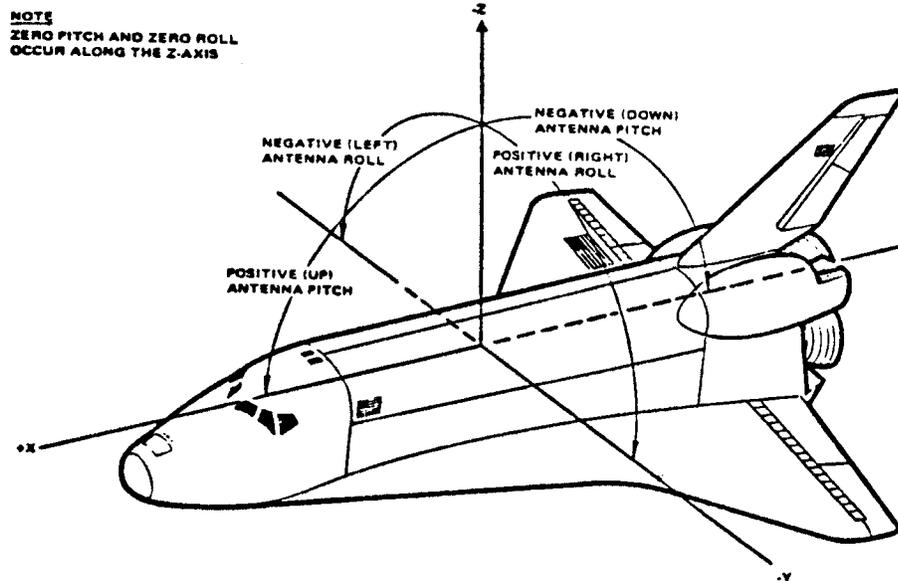


Figure 2-16.- Orbiter vehicle coordinate system and Ku-band antenna slewing directions.

Radar EL and AZ are the target LOS angles which provide the crew with the antenna position relative to the Orbiter $-Z$ axis. Assuming radar TRK and Orbiter attitude with $-Z$ axis parallel to V-BAR, then EL and AZ provide an indicator of Orbiter position relative to TGT V-BAR (since at close ranges the TGT V-BAR and Orbiter V-BAR essentially coincide), and consequently the thrusting direction required to drive back the TGT V-BAR. These angles are useful primarily during the night side of the orbit, when the TGT is not visible in the COAS.

2.5.4.2 COAS Azimuth

COAS azimuth is the horizontal position (Orbiter Y, Z plane), in degrees, of the TGT position in the COAS FOV relative to the Orbiter $-Z$ axis. This is assuming the COAS is properly aligned. Whenever the $-Z$ axis is aligned parallel to the V-BAR with the Orbiter X axis in the TGT orbital plane, this angle provides an indication of the $\pm Y$ axis thrusting required to drive the Orbiter back to the V-BAR.

2.5.5 Elevation Rate

Elevation rate (EL-DOT) is the pitch inertial angle rate. Positive sense is toward the $\pm X$ Orbiter axis.

2.5.6 Azimuth Rate

Azimuth rate (AZ-DOT) is the roll inertial angle rate. Positive sense is toward the -Y Orbiter axis.

EL-DOT and AZ-DOT are the components of the inertial angle rate of the Orbiter-TGT LOS, transformed into the Orbiter X, Z and Y, Z body planes, respectively.

2.6 TARGET VISIBILITY

Of great concern to naked-eye observation of a TGT is its illumination, its position relative to the Sun, and its position relative to the horizon.

2.6.1 Illumination

The portion of an orbit in which a TGT is lit by the Sun can range from little more than a half all the way to total (100 percent). This is a function of target altitude, inclination, and beta angle. Sunlit (passive) illumination is critical for COAS and STRK observation.

2.6.2 Position Relative to the Sun

Looking toward the Sun makes observing a TGT very difficult, both from the direct solar glare, the glare induced on the windows, and the fact that it is the nonilluminated side of the TGT facing the observer. No observations are generally planned when the TGT is within 20° of the Sun, but glare conditions certainly exist even farther out.

Preferred operating relative positions (assuming low beta angle) are with the Sun behind the observer, or off to the side of the observer-TGT line of sight. For a situation with the Orbiter ahead of the TGT, this is satisfied in the period between orbital sunrise and orbital noon; for an Orbiter behind a TGT, the interval is approximately orbital noon to sunset. This geometry is taken into account during operations planning.

It is also generally preferred that the TGT be a diffuse reflector rather than a "shiny" specular reflector. Because diffuse reflection provides more uniform reflection at all angles, there is less concern for loss of TGT visual for certain TGT attitudes relative to the LOS. Specular reflection is particularly obvious from solar panels tracking the Sun.

Terminal phase of the rendezvous profile is designed to optimize lighting conditions. As seen in figure 2-17, the LOS to the Sun is kept far from the target LOS.

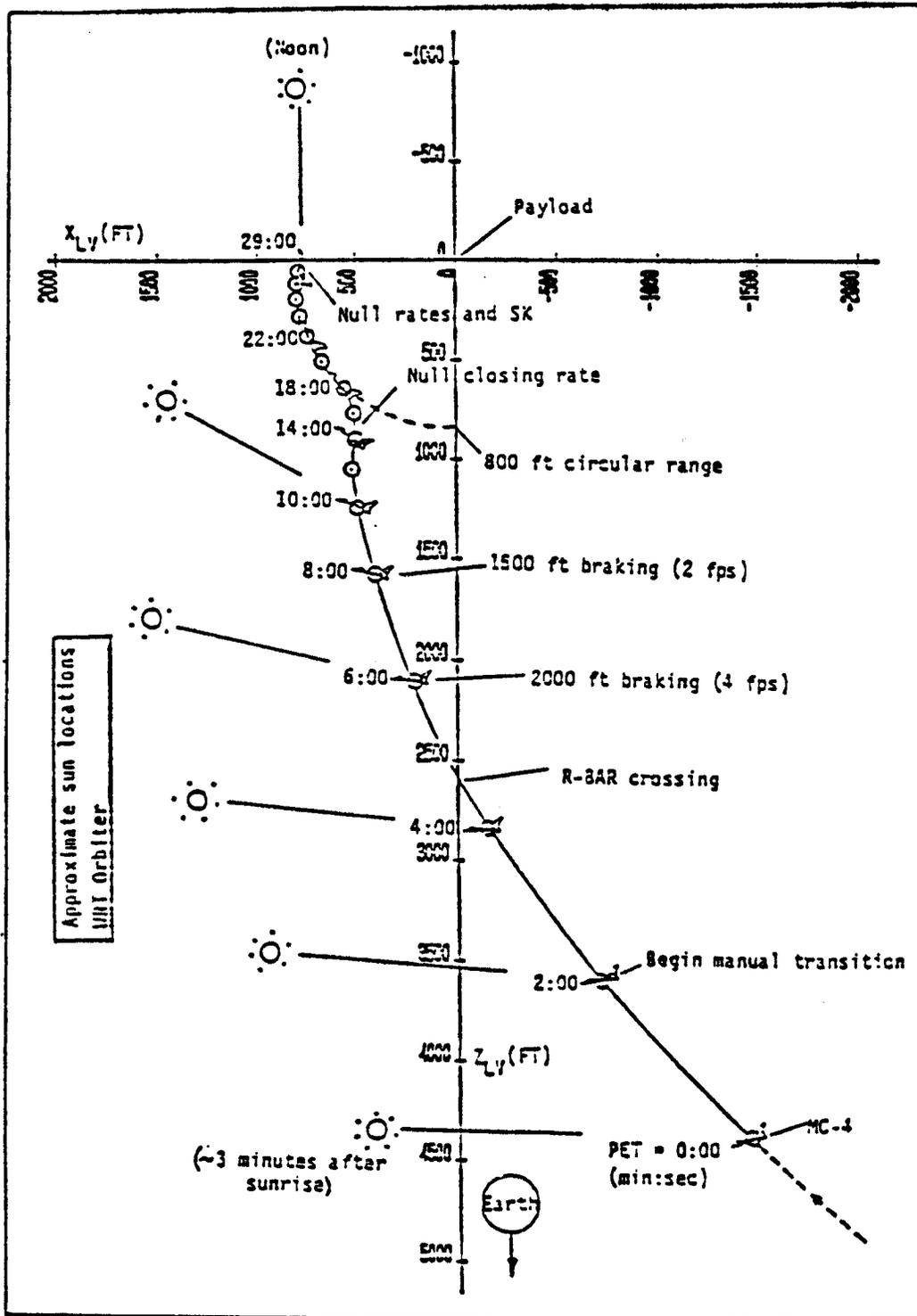


Figure 2-17.- Angle to sun during terminal phase (note: disregard obsolete procedure at 800 feet).

2.6.3 Position Relative to Horizon

The angle between the Orbiter-centered LVLH "horizontal" vector and the Earth horizon is a function of Orbiter altitude. Because of the altitude of the Orbiter, the Earth horizon lies significantly below the "horizontal" vector. The amount of depression is shown in figure 2-18. This becomes important during periods of attempted observation when the Orbiter is at a higher altitude than the target. Both eyeball (including COAS) and ST visibility are adversely affected near and below a sunlit horizon.

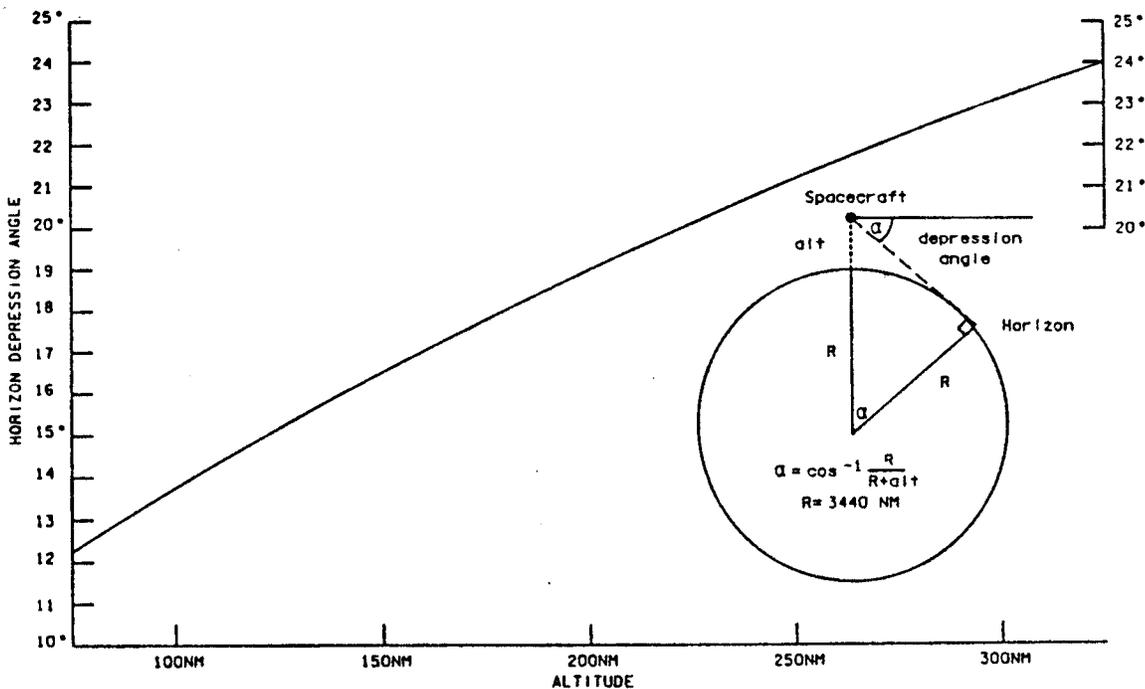


Figure 2-18.- Horizon depression angle as a function of Orbital altitude.

2.7 OTHER FORCES

Several other forces affect the relative orbital motion of satellites. Both atmospheric drag and Earth oblateness will affect satellites differently depending mainly on their altitudes.

2.7.1 Differential Drag

Differential drag effects can produce unexpected relative motions or can be utilized productively (particularly in gentle separation MNVR's). Typical differential drag effects are shown in figures 2-19 A and B.

The atmospheric drag on a satellite is a function of satellite size, mass, geometry, attitude, and orbital altitude. Two nearby satellites usually have some difference in atmospheric drag. If the difference is small, it

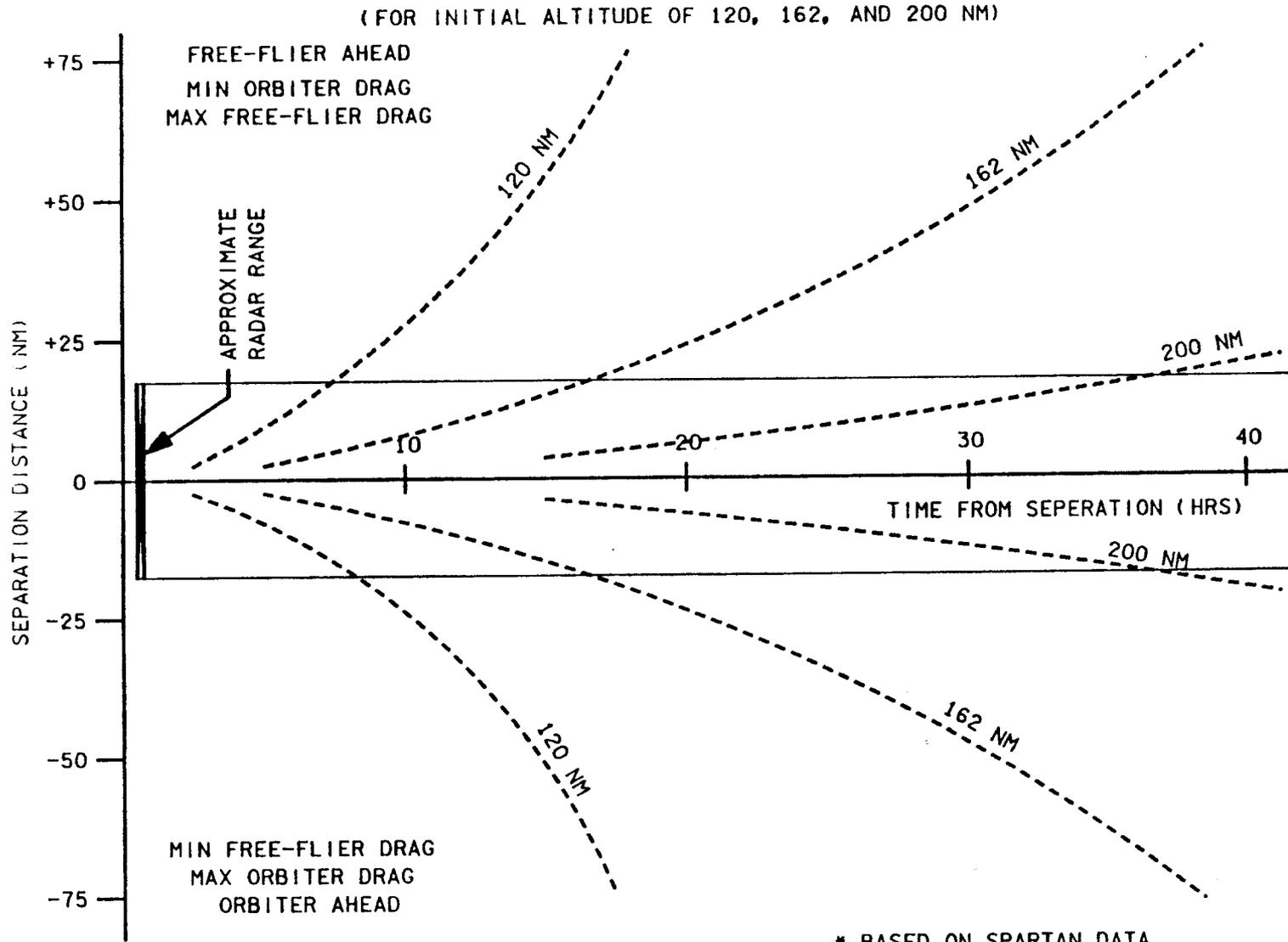


Figure 2-19A.- Illustrative differential drag effects, Orbiter and small free-flier,* as function of orbital altitude.

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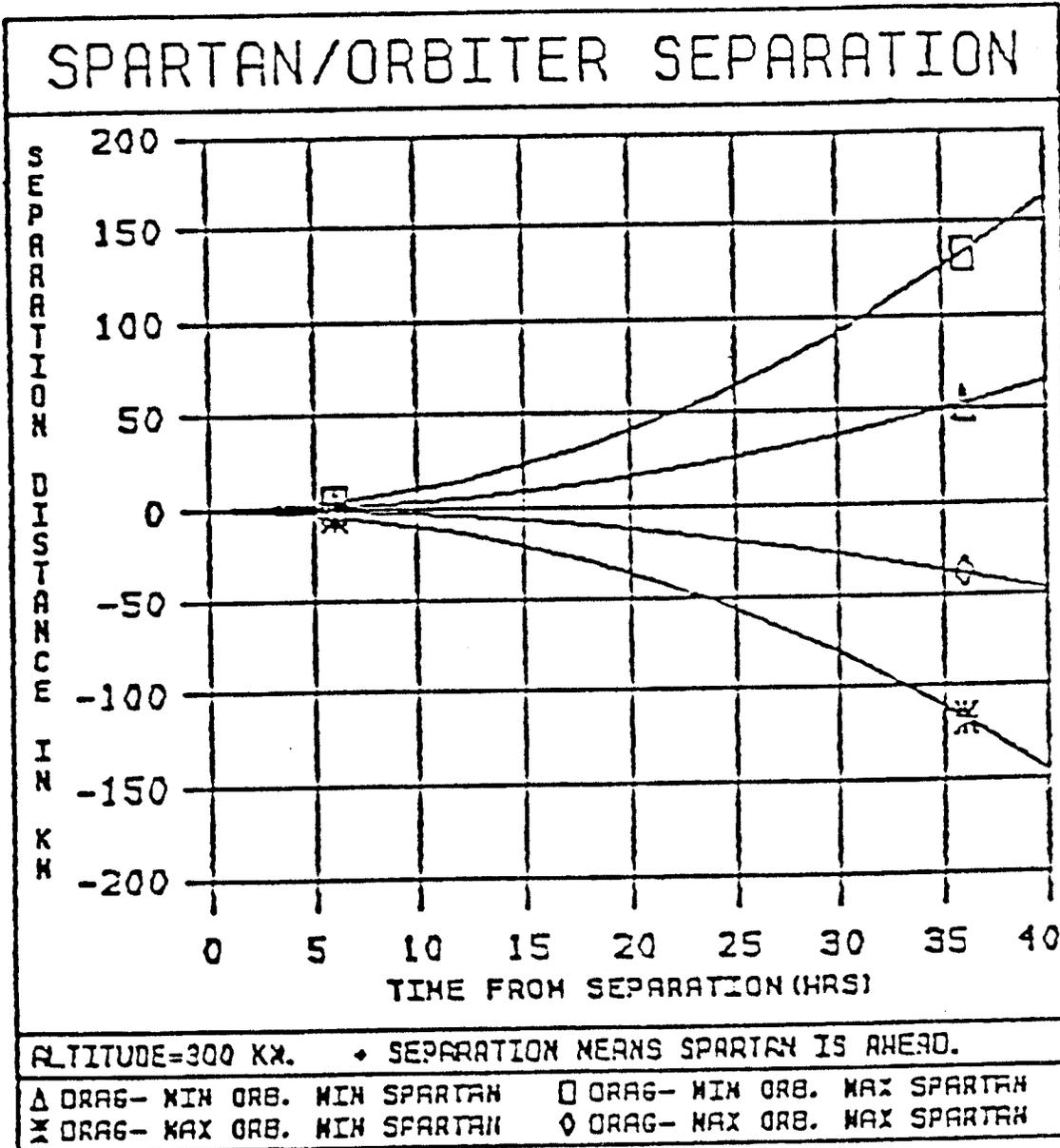


Figure 2-19B.- Drag effects on function of Orbiter and payload attitude variations.

can be ignored; if it is large, it can introduce separations of thousands of feet per REV.

For differential drag effects, atmospheric density is the same for both objects. Typically, since volume is proportional to the cube of radius while area is proportional to the square of radius, and since deceleration due to drag is proportional to area divided by mass (which is directly related to volume for a constant mass density), then in general the larger the body the less significant the drag effects if the density of the 2 vehicles is about the same. For non-symmetrical objects, attitude is also important since the frontal area affects drag (e.g., the Orbiter in XLV Y-POP has about three times the drag as the Orbiter in ZLV Y-POP).

For example, a 1-meter diameter tracking sphere weighing 34 pounds would pull ahead of the Orbiter by 3 miles per REV and drop about 1 mile per REV, at 160 n. mi.; at 120 n. mi., it would pull ahead by 15 miles per REV while dropping 4 miles. Figures 2-19 A and B show typical SPARTAN-class differential drag effects.

Another example of how differential drag can cause motion which seems contrary to "common sense" is a case involving a spacecraft which has very low density particles (e.g., "snowflakes") separating from it. Drag will quickly cause the particles to lose energy and fall into a lower orbit where they will pick up speed and pull ahead of the spacecraft. An example of this was MA-6 in 1962. From the spacecraft, ice particles appeared to be accelerating away forward, which in one sense they were, because their drag was greater than that of the spacecraft. Understandably, this was not obvious at the time, and the motion of the particles (the "fireflies") caused some bafflement.

2.7.2 Differential Nodal Regression Effects

The oblateness of the Earth causes the orbital plane of a satellite in posigrade orbit to be displaced westward by several degrees per day. The magnitude of this displacement is affected by orbital inclination and altitude (orbits with steeper inclinations and/or higher altitudes are less affected by the perturbing force of the oblate mass). See figure 2-20.

Through an equation derived from geophysics principles, the precession rate (in degrees per day) can be calculated:

$$\text{rate} = -9.98 (\cos i) (r/a)^{3.5}$$

where r = Earth radius
 a = orbital semimajor axis
 (assuming low eccentricity)

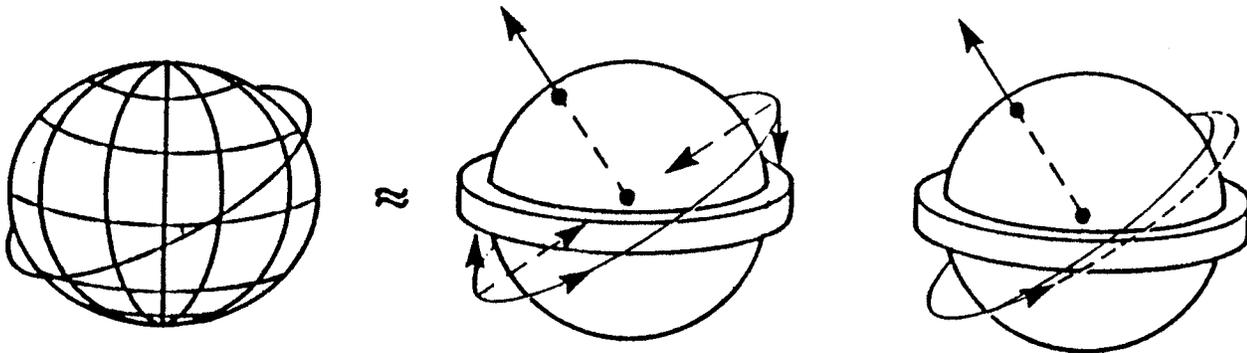


Figure 2-20.- Plane shift due to equatorial bulge.

Two near-coplanar orbits with different altitudes will have different nodal rates, and hence a relative differential rate. The lower orbit will precess faster relative to the higher orbit. These effects are small: at 28° and about 150 n. mi., the differential rate is about 27 ft. per REV per 1000 ft. of average altitude separation. This effect is accounted for in both ground and onboard RNDZ targeting; this effect is small enough to be disregarded in all RNDZ manual phase and PROX OPS maneuvering.

2.8 TYPES OF RENDEZVOUS MANEUVERS

Specific terminology has evolved which is applied to different types of rendezvous maneuvers. The "N" preceding the maneuver type once referred to the REV number of the maneuvers (orbits on which they were executed, counted from the ascending node); subsequently it became a meaningless and redundant designator. Note that the following descriptions pertain to the standard STS stable orbit rendezvous (SOR) profile.

2.8.1 Generic NC, or Phase Adjust (or "closing")

This is a horizontally executed MNVR targeted to obtain the desired offset position from the target (phase angle) at a future time. It controls the X axis curvilinear distance. It is a ground-targeted burn. There usually are more than one such burn. The phasing maneuver (NC) burns typically adjust catchup rate by adjustment of orbital period. They accommodate the phasing at the actual time of launch.

2.8.2 Generic NH, or Differential Height Adjust (HA)

This is a horizontally executed MNVR targeted to a differential height from the TGT at some future time. It controls the Z axis distance. It is ground targeted

2.8.3 Generic NPC, or Plane Change

This is an out-of-plane MNVR which places the chaser into the phantom plane of the TGT. The phantom plane is the actual plane of the TGT offset by the amount of differential nodal regression calculated to occur between the MNVR and the desired inplane time. In addition, the MNVR must be located at a common node between the chaser and phantom TGT planes. If the future time to be inplane is not identified, the MNVR will place the chaser in the actual plane of the target at the time of the MNVR. This burn controls the Y axis distance. It is ground-targeted.

2.8.4 Generic NCC, or Corrective Combination

This is a Lambert-targeted MNVR to correct the chaser trajectory to achieve a desired offset position from the target. It controls all axes. This MNVR is a combination of three MNVR's: NC, NH, and NPC. It is ground targeted and also targeted onboard with Orbiter sensor data.

Note that in general it is very advantageous to combine orbit adjust burns and plane changes, since they are perpendicular to each other and the resulting burn is an RSS combination, which is usually much more economical than making each burn separately. However, this may not be possible if the maneuver is to be located at an orbit apsis and a common node.

2.8.5 Generic NSR, or Coelliptic

This is a MNVR targeted to put the chaser in an orbit coelliptic to the TGT. Coelliptic is defined as a condition where there are coincident lines of apsides and equal differential altitudes at both apogee and perigee. The "SR" of "NSR" once stood for "Slow Rate."

2.8.6 Generic Ti, or Transition Initiation (Ti)

This is a Lambert-targeted MNVR which places the chaser on an intercept trajectory with the TGT. It occurs several minutes before noon. It is targeted for 320° transfer, to achieve "hot" closing trajectory and maintain good lighting for manual braking and proximity operations. Do not confuse "Ti" with the "T1" designation used in orbit targeting; their similarity is an unfortunate coincidence.

2.8.7 Generic MC, or Midcourse

These are also Lambert-targeted maneuvers placing the chaser on an intercept trajectory. Each midcourse MNVR corrects minor dispersions using more and more accurate tracking data.

Note that in general, a midcourse will be made as it is realized that intercept will not occur. If it is farther than expected, the Orbiter must go faster, and this is done by entering a lower orbit, so the midcourse direction is downwards; if the target is closer than expected, the Orbiter must slow down by entering a higher orbit, and this is done by performing a midcourse correction upwards. Other requirements are second-order effects. Note that we are talking about only fractions of one complete revolution from the actual midcourse maneuver point until final intercept; in the long-term, such up and down burns do not, of course, alter the total orbital period, but they can and do alter the speed of the chaser along portions of each revolution.

2.8.8 Generic TF, or Transition Finalization

This is the second maneuver of the Lambert pair T_i - TF (or MC-TF). This MNVR is designed to null the relative rates between the TGT and chaser at the intercept point. It is not a guided MNVR executed by the crew. However, the braking gates and the V-BAR stabilization burn cumulatively approximate a "TF burn." The term "TF" does not appear in the actual FDF.

2.9 TYPICAL RENDEZVOUS

The RNDZ is performed by making MNVR's and sensor passes.

2.9.1 Maneuvers

A typical RNDZ plan involves a series of maneuvers of the types described above. Figure 2-21 shows typical relative motion for a ground-up RNDZ profile. A typical on-orbit RNDZ profile can be seen in figures 4-1, 4-2, and 4-3.

The highest "humps" in the trajectory of the chaser represents the relative apogee between the TGT and chaser vehicles; if the TGT is in a circular orbit, this will also be the apogee of the chaser. The lowest "humps" in the trajectory of the chaser represent the relative perigee between the TGT and the chaser vehicles. If the TGT is in a circular orbit, this will also be the perigee of the chaser.

From peak to peak is one revolution (from relative apogee to relative apogee).

Phase angle and differential height (DH) are both noted on the figure.

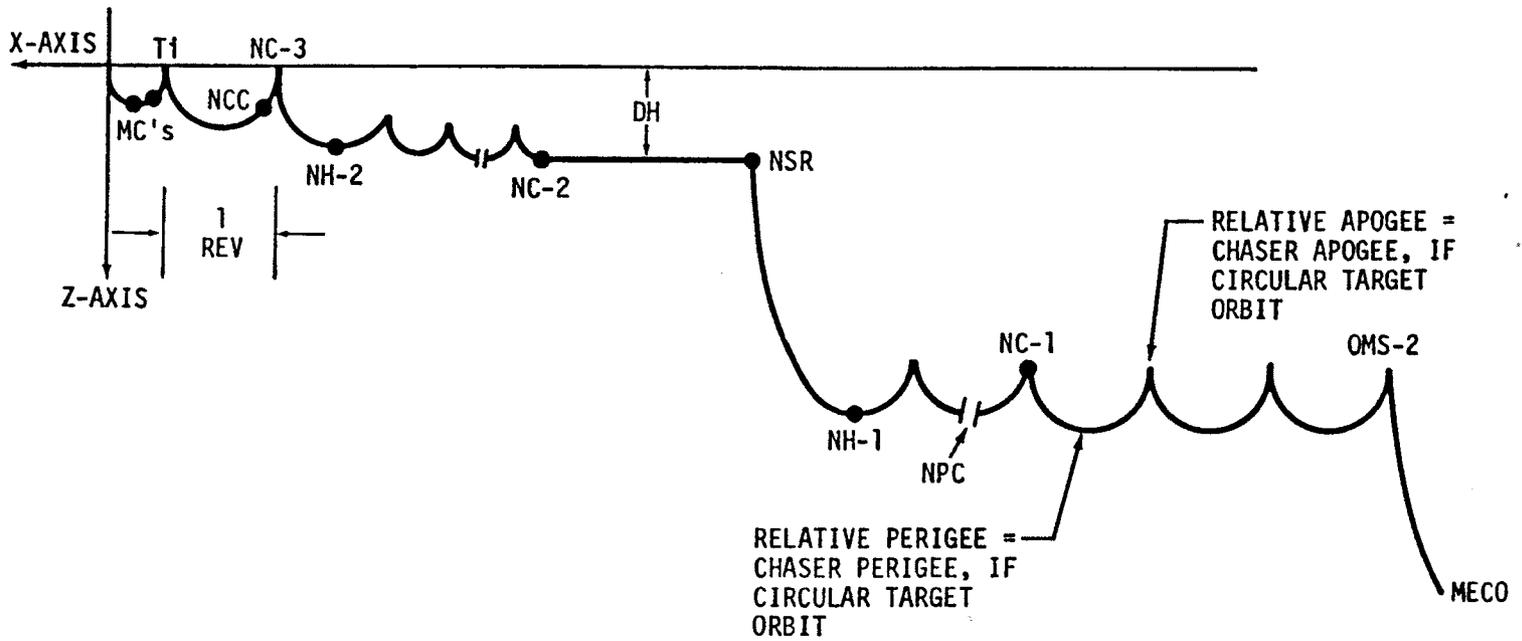


Figure 2-21.- Typical target centered relative motion (ground-up rendezvous).
 Distance behind along X axis is proportional to PHASE ANGLE (0).

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2.9.1.1 The Actual NC Maneuver(s)

Most RNDZ plans will contain several NC MNVR's, the first one being OMS-2. Typically, the flight dynamics officer (FDO) will try to schedule at least one NC MNVR per flight day. The reason for multiple NC MNVR's is that they control the X axis (downtrack) distance; this is the direction that is affected most by attitude maneuvers, water dumps, mis-modeled drag, and propagation errors because of the secular effects. Radial and out-of-plane disturbances induce periodic (cyclic) motion.

The phasing profile has a great effect on the available launch window.

2.9.1.2 The Actual NH Maneuver(s)

Usually there is at least one NH maneuver in the RNDZ profile, that maneuver controlling the relative distance to the target altitude. Some profiles will contain multiple NH maneuver, if there are intermediate altitudes that need to be achieved.

2.9.1.3 The Actual NSR Maneuver

There is usually only one NSR maneuver in the RNDZ profile, although there could be more. It is desirable to go coelliptic with the target so that future maneuvers may be initiated based on orbital lighting.

2.9.1.4 The Actual NPC Maneuver

There is typically one NPC maneuver in each RNDZ profile so that the Orbiter will be inplane with the TGT at the desired time. This applies mostly to ground up RNDZ plans, since its primary purpose is to remove ascent planar dispersions.

Other than being executed at a common node, placement of the NPC maneuver is completely arbitrary since it is designed to put the Orbiter inplane with the TGT vehicle at T_i .

2.9.1.5 The Actual NCC Maneuver

There is only one NCC maneuver which is targeted with the onboard computers after some sensor data has been obtained (it is also targeted on the ground). It occurs 225° (about one hour) before T_i , and aims for a point 48,600 feet (8 n. mi) trailing and 1,200 feet above the V-BAR, inplane with the TGT.

2.9.1.6 The Actual Ti Maneuver.

There is only one Ti - TF combination to initiate transition to manual phase. It begins three minutes before orbital noon, at a time determined by the ground, and spans a 320° transfer to intercept. Current strategy places this burn near orbiter apogee.

2.9.1.7 The Actual Midcourse Maneuver(s)

There can be up to four midcourse maneuvers. MC1 is about 8 minutes before sunset; MC2 is at a 28.5° elevation angle to the target and is targeted with a 125° transfer to target intercept.

2.9.1.8 The Actual TF Maneuver

This would theoretically occur about 10 minutes after MC4, but before that point, the final orbit-matching burns are made manually based on range rate and out-the-window LOS to target. A generic TF burn is not targeted or performed.

2.9.2 Out of Plane Control Theory and Practice

There will always be an initial planned planar separation between a chaser orbit and the target orbit. Propulsive burns are designed to reduce unplanned out-of-plane motion to zero at final approach. Some aspects of this strategy were described in passing in the previous sections, but this section addresses the issue directly and exclusively.

Section 3.5.7 discusses several aspects of using the ORB TGT function to assist in out-of-plane control on the day of rendezvous.

2.9.2.1 Initial Conditions

Between any two orbital planes there is a line of nodes which is defined by the intersection of those two planes. That line moves naturally due to orbital mechanics effects such as differential nodal regression, if the two orbits have different altitudes. Usually the chaser is in a lower orbit, and its strategy is to move into a phantom plane which itself will shift into the actual target plane due to these orbital mechanics effects. See figure 2-22.

Initial OOP dispersions are due mainly to ascent yaw steering for ground-up RNDZ's and to IMU alignment or maneuver trim errors on deploy/retrieval RNDZ's.

Reserved for Fig. 2-22

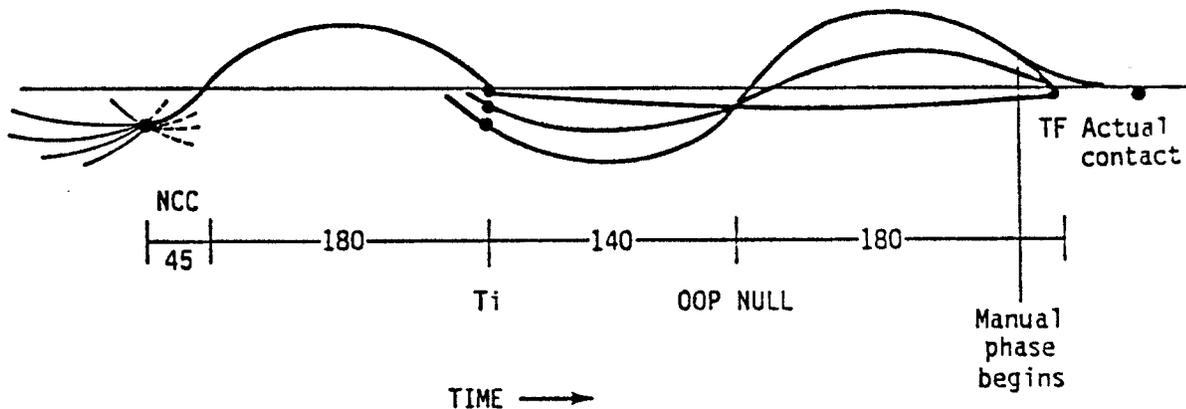


Figure 2-22.- Out-of-plane-motion.

2.9.2.2 Early burns

Long prior to the final rendezvous, an NPC burn (there can be more than one) occurs with the specific purpose of providing a zero Y and Y-DOT at Ti. To save propellant, designers (pre-flight) and flight controllers (real time) try to combine a portion of these NPC burns (with a pure Y component) with other maneuvers such as NC, NH, or NSR burns which nominally have no planar functions (and thus no Y components). The consequent RSSing of two such burns results in both being achieved for a delta-V substantially less than their linear sums.

2.9.2.3 NCC

NCC attempts to place Ti in plane to the best of NAV's knowledge: to place the Ti burn at node (Ti TIG is when the chaser crosses the target plane). This burn thus drives the chaser back through the orbit plane in about 11 minutes. See figure 2-22, which shows various approach trajectories to the NCC point versus a unique post-NCC trajectory.

2.9.2.4 Ti

If NCC is targeted and executed perfectly, Ti occurs in the target plane (i.e., at a node) and with perfect Ti targeting and execution the Orbiter remains inplane from then on. In the real world this usually doesn't happen (NCC is targeted and executed imperfectly, so Ti TIG occurs somewhat out of plane) and there will be further OOP motion. To set up the desired final

approach conditions, the next node must be set to a point 140° ahead, so final intercept ("TF") then occurs in plane after 320° ($140^\circ + 180^\circ$) of travel. This aim point, TF, is where the chaser would physically intercept the target if no manual braking burns occurred; it would occur at about MC4 + 10, with a relative velocity of about 5 ft/s, approaching relative apogee (but not yet there). Naturally, manual phase operations (e.g., braking gates) slow the final approach well before this point and thus significantly delay contact beyond this time. If there is any OOP motion at TF, it must be detected out the COAS or on RR angle rates, and nulled manually. Usually, however, the Orbiter and target are essentially coplanar by this point.

Because of NAV dispersions and NCC trims, Ti TIG usually occurs at some nonzero Y point (i.e., measurably off the target plane). In that case, to achieve the desired mode 320° (and also 140°) in the future the Ti Y component will push the chaser away from the target plane (it may already be headed away), and maximum separation will occur 50° (about 12 minutes) after Ti TIG. The size of this maximum separation is proportional to how far the Ti burn turned out to be out of plane (fig. 2-22 shows this effect).

Since MC1 is also targeted to the same node as Ti was, it does not significantly alter the subsequent nodes, if REL NAV supporting Ti and Ti trimming was very good.

2.9.2.5 OOP Null

The final node prior to TF occurs about halfway between MC1 and MC2 (nominally, MC1 + 13 minutes). At this point, relative navigation data displayed to the crew on SPEC 33 is used to perform the burn: first, the crew notes the actual in-plane time (Y becomes zero), and then the crew monitors the proper size of their manual RCS burns made to prevent further out-of-plane swings (Y-DOT is driven to zero). The burn can be made over a span of several minutes without seriously impacting the out-of-plane situation.

If this burn is not performed properly, the same Y-DOT can and must be manually removed half a REV (45 minutes) later, post-MC4, with the crew in the manual phase (nominally, RR data allows NAV to produce reliable Y and Y-DOT values, and the target can also be viewed out the COAS). This correction can also be facilitated by knowledge of the former Y-DOT at the missed OOP point or by nulling OOP rates as soon as possible after the nominally scheduled time.

Procedural matters for executing this burn are discussed in section 4.1.54 (and fig. 4-14).

2.9.2.6 Proximity Operations

For final approach, and for stationkeeping, plane control is an entirely manual function based on visual/RR LOS motion. The crew should have the OOP situation under control by V-BAR arrival, and certainly by the time DAP LOW Z is entered. The best method is to use small THC pulses to start the target moving toward the center of the COAS and then, as it crosses the centerline, input an equal number of pulses in the opposite direction to stop the motion.

Any remaining Y-DOT is of sufficiently small scale that it causes essentially no orbital mechanics effects (the short time scale of PROX OPS maneuvering also induces this) and therefore "OOP" (any Y components of relative position) now can be handled as pure inertial relative motion and corrected directly as detected.

2.9.3 Typical Sensor Passes

Prior to the first acquisition on by on-board sensors, all information on the Orbiter-target relative state is computed (both on the ground and on-board) from separate inertial Orbiter and target SV's produced by ground tracking; the onboard SV's are uplinked from the MCC (the target SV is not used on board until entry into RNDZ NAV). To facilitate accurate ground NAV (and hence the best possible SV's), there can be periods when some Orbiter activities may be restricted to the extent of avoiding propulsive activities such as vents, excessive attitude maneuvering, and water dumps.

The strategy of onboard sensor passes is to progress to successively more precise knowledge of the Orbiter-target relative state by use of a sequence of sensors and appropriate navigation software (see fig. 2-23).

Note that sensor data history (when and if data was acquired and how many marks were received) is one of the two criteria for when to abort the RNDZ (see section 4.4); propellant is the other criteria.

2.9.3.1 First On-board Acquisition

Prior to NCC, 2 sensor passes are desired (typically star tracker) to support the first onboard targeted MNVR, NCC. These sensor data reduce errors in the relative state caused by ground tracking inaccuracies, maneuver trim errors, translational cross-coupling, and trajectory dispersions.

The fault-down philosophy for these sensor passes is:

- -Z Star tracker
- -Y Star tracker
- COAS

2.9.3.2 Radar Acquisition

Between corrective combination MNVR (NCC) and T_i , RNDZ radar data is available to support the T_i computation. There is no fault-down during this time period because the Orbiter is between sunrise and noon, looking toward the Sun.

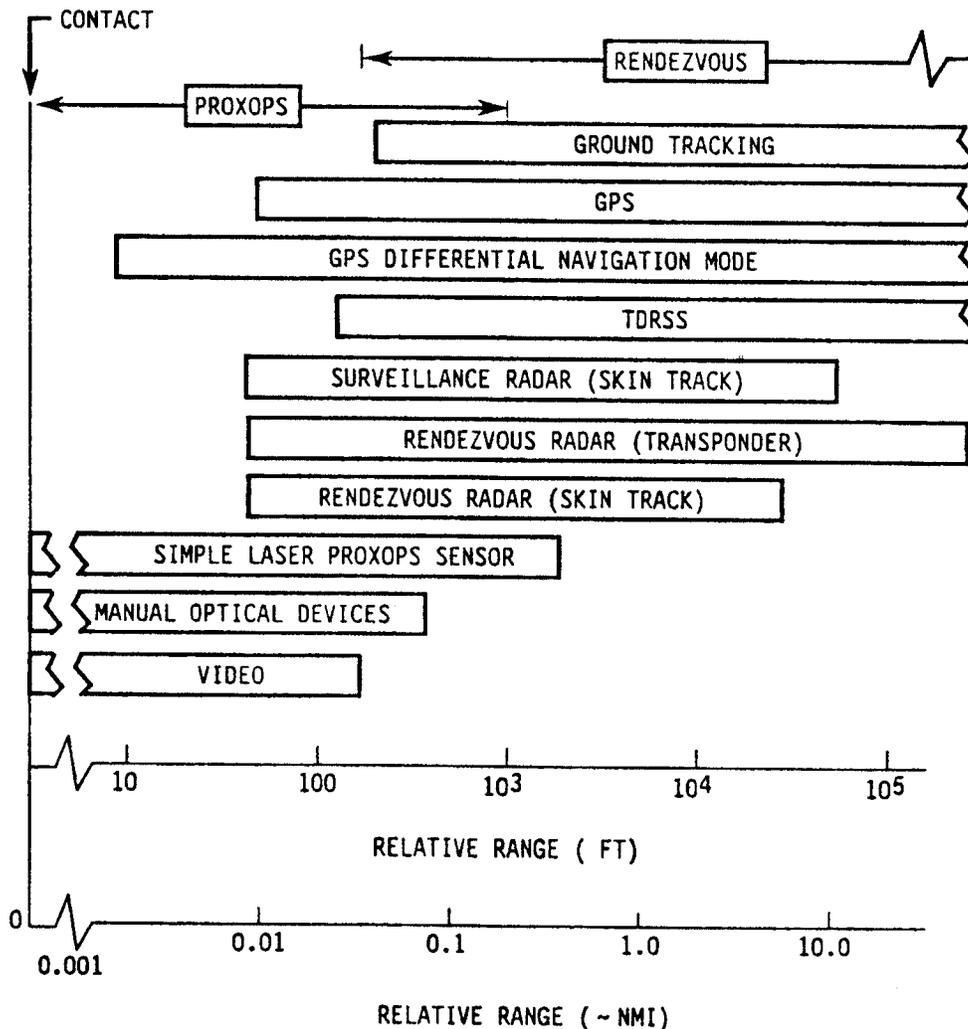


Figure 2-23.- Spectrum of rendezvous sensors.

10589*006

2.9.3.3 Final Sensor Acquisitions

After T_i , as much sensor data as possible is desired to support the midcourse corrections. The general fault-down philosophy is:

- Rendezvous radar
- -Z star tracker
- -Y star tracker
- COAS

2.10 Pre-Day-of-Rendezvous Navigation

An appreciation of the impact of pre-day-of-rendezvous ground tracking on support of the initial conditions on rendezvous day (in particular, state vectors) can be useful in understanding certain constraints on the timeline. This afterthought is meant to complete this handbook's discussion of RNDZ NAV issues.

Generic NAV accuracies and rendezvous tracking requirements are defined in NSTS 07700, VOL XIV, Appendix 6. These are considered to be very conservative. Mission-specific analyses always are performed for rendezvous flight design. Specific target-related tracking requirements will be in specific PIP's. Detailed ground procedures and NAV-related information can be found in "ON-ORBIT GROUND NAVIGATION CONSOLE HANDBOOK", JSC IN # 20768, and in the "FDO CONSOLE HANDBOOK", from which the following treatment is adapted.

The philosophy for rendezvous is to go into any maneuver or targeting phase with the best possible state vector, especially as the day of rendezvous approaches. Every additional tracking site provides more data to update the ground's knowledge, and will be utilized even if it is the first station after a maneuver. Phasing between the chaser and the target is the hardest dynamic process to control, and this requires precise knowledge of the object's semimajor axis (and hence its period). That element must be periodically determined (requiring several REV's of quiet tracking) and then adjusted as needed with an NC burn.

Although there is no single pre-defined tracking arc for a rendezvous profile, the FDO's will be trying to have fresh Orbiter and TGT SV's prior to the preliminary maneuvers plan. The TGT SV tends to change very little with time (typically there are no attitude maneuvers, vents, etc.), so a SV which is several REV's old is still considered adequate for computations. But the quality of the Orbiter SV can depend on particular on-orbit crew activities.

The main unmodeled perturbations on the Orbiter's trajectory are attitude maneuvers. It is thus desirable to minimize them on the evening before rendezvous day, after that day's NC phasing burn. This means eliminating standard IMU alignments (which require an attitude maneuver that cross-couples into unwanted translation). IMU alignments can be accomplished instead by taking stars of opportunity during the sleep period with the Orbiter nose in a north or south orientation.

Water dumps introduce small impulses, so they cannot be permitted prior to critical maneuvers unless the induced SV errors can be tracked out before the maneuver computation. The effects of water dumps on Orbiter trajectory have not been predictable. An alternate procedure is to run the flash evaporator (FES), which has very little effect on trajectory.

By observing these constraints, the Orbiter will hit the desired offset on rendezvous morning for the last NC burn before T_i , and the FDO won't get any trajectory surprises. Following several more periods of intensive ground tracking of both vehicles, the Orbiter itself will begin on-board tracking of the target (see section 2.9).

SECTION 3
TOOLS FOR RENDEZVOUS

Performance of orbital RNDZ and PROX OPS is enabled by numerous hardware and software tools on the Orbiter. This section is a summary of their capabilities and basic operational characteristics relevant to RNDZ and PROX OPS usage. Discussion is intended to be more detailed than in other available literature, but also more narrowly focused. Subsequent sections will discuss specific applications of these tools to real RNDZ and PROX OPS profiles.

The material in this section, both tool descriptions and general procedures for use of those tools, can be considered "subroutines" for sections 4 and 5, which consist of specific procedures rationale narratives for RNDZ operations (section 4) and PROX OPS (section 5).

3.1 ATTITUDE DETERMINATION/CONTROL

For determination and control of Orbiter attitude, the crew uses the OPS 201 display (Universal Pointing), along with the attitude direction indicator (ADI) and the hand controllers.

3.1.1 Universal Pointing (UNIV PTG, or UP) (OPS 201)

UNIV PTG (fig. 3-1) is the MM 201 display and provides the crew with four mutually-exclusive options for automatic (AUTO) attitude control with respect to the forward (+X) ADI reference frame. Three options are universal

```

2011/ / UNIV PTG XX X DDD/HH:MM:SS
CUR MNVR COMPL XX:XX:XX DDD/HH:MM:SS
1 START TIME XXX/XX:XX:XX
MNVR OPTION START MNVR 18 X X
5 R XXX.XX TRK 19 X X
6 P XXX.XX ROT 20 X X
7 Y XXX.XX CNCL 21

TRK/ROT OPTIONS ATT MON
8 TGT ID XXX 22 MON AXIS X XX
ERR TOT 23X
ERR DAP 24X
9 RA XXX.XXX
10 DEC ±XX.XXX
11 LAT ±XX.XXX ROLL PITCH YAW
12 LON ±XXX.XXX CUR XXX.XX XXX.XX XXX.XX
13 ALT ±XXXXX.X REQD XXX.XX XXX.XX XXX.XX
ERR ±XXX.XX ±XXX.XX ±XXX.XX
14 BODY VECT X RATE ±XX.XXX ±XX.XXX ±XX.XXX

15 P XXX.XX
16 Y XXX.XX
17 OM XXX.XX

```

(XX)

Figure 3-1.- The UNIV PTG (OPS 201) display.

in that they are defined by data inputs made by the crew. The other option is a cancel option that holds the inertial attitude that is current at the time the option is selected. It terminates any other current or future AUTO option. These options are accomplished automatically only if the digital autopilot (DAP) is in AUTO.

The first option is the maneuver (MNVR) option. It allows the crew to maneuver the Orbiter to a specified inertial attitude at a specified start time.

The second option is the tracking (TRK) option. It allows the crew to orient the Orbiter to point a specified body vector at another orbiting vehicle, an Earth target, center of Earth (for local vertical local horizontal (LVLH) hold), center of Sun, or a celestial target (specified coordinates or target navigation star number) at a specified start time.

The third option is the rotation (ROT) option. It allows the crew to rotate (always clockwise) the Orbiter inertially about a specified body vector at the DAP selected rate, beginning at a specified start time.

The fourth option is the cancel (CNCL) option. It allows the crew to deselect any other option and hold attitude automatically about the existing inertial attitude at the time the cancel option is selected.

Also provided is the capability to monitor vehicle attitude parameters in roll, pitch, and yaw body coordinates.

3.1.1.1 Options

For detailed explanation of the general capabilities of UNIV PTG, see the Attitude/Pointing Flight Procedures Handbook (JSC-10511). The following discussion is concentrated on the specific use of UP in RNDZ and PROX OPS.

- a. CUR MNVR COMPL - The current maneuver completion (CUR MNVR COMPL) time is shown in hrs:mins:secs when a maneuver (MNVR or TRK) is in progress until the attitude is within 1° of desired, at which time it is frozen. The time is also frozen if a maneuver is in progress and the DAP LVLH mode is selected. Time is reset to zero if a maneuver is in progress and CANCEL is selected. The completion time remains unchanged if a maneuver is not in progress and the DAP MAN or LVLH, or ROT option, or CANCEL is selected.
- b. START TIME (items 1 through 4) is designated in days/hrs:mins:secs mission elapsed time (MET) for the selected control option. Display is initialized with the time at zero.
- c. TRK/ROT OPTIONS - Item 8 selects the TGT identification for the TRK option. "Orbiting Vehicle" is ID number 1 and center of Earth is number 2; the LOS is determined from the SV's of the Orbiter and the TGT vehicle. Item 14 selects the body vector (BODY VECT) which is pointed

along the LOS for the TRK options. The BODY VECT identifiers are as follows:

- 1 is +X ;
- 2 is -X ;
- 3 is -Z ;
- 4 is PTC (passive thermal control), about 2° below +X;
- 5 is Selectable, using items 15 and 16 to define the BODY VECTOR. (P and Y must be positive.)

NOTE: In practice +X is used for PTC ROT's, instead of PTC axis.

Any attempt to load other identifiers will result in an illegal entry message. The identifier will be initially loaded with 1 (one).

Item 17 selects the omicron angle desired for the TRK option. With this item, the user can specify the attitude orientation of the Orbiter about the selected body pointing vector used in the TRK attitude option. A precise definition of "omicron" is found in the Attitude/Pointing Flight Procedures Handbook.

The omicron item is blanked when a new TGT ID is entered. If the item is still blank when the TRK attitude option (item 19) is selected, two-axis TRK will be implemented. In this mode, the Orbiter-selected body-pointing vector is aligned with the TGT LOS with a minimum attitude change in which the maneuver transfer angle (often called "eigenangle") is minimized. This means that the Orbiter will track the TGT with the specified TRK body vector, but that the Orbiter orientation about that body pointing vector (omicron) will not be fixed. Instead, it will vary such that the total required rotation is minimized. If an omicron-angle restraint is input in item 17 and the TRK option is selected, three-axis TRK will be used. In this mode, both the pointing requirement and the omicron-angle constraint are imposed in making computations.

If omicron is not blank, entering a body vector ID in item 14 initiates the flashing of omicron. The flashing is terminated when a value of omicron is entered or when an attitude option is selected.

The allowable range for omicron is 0° to 359.99°. User input outside this range results in an ILLEGAL ENTRY message. The value of omicron is initialized to zero, and three-axis TRK is selected.

- d. START MNVR, TRK, ROT (items 18, 19, 20) provide selection of the MNVR, TRK, or ROT control option. Initiation of a control option depends on the START TIME entered in items 1 through 4. If the START TIME is zero, current (CUR), or in the past and DAP is AUTO, the control option is initiated upon selection, a "*" appears in the CUR column next to the selected option, and any other option is deselected (no "*"). If the START TIME is in the future, the selected control option is initiated at that time and in the interim a "*" appears in the future (FUT) column

next to the selected option. The selected option in progress ("*" in the CUR column) drives the REQD attitude, ERR, and the ADI error needles.

Control option initiation must be preceded by DAP AUTO. If a future start time is within 30 seconds of current time and AUTO has not been selected, a class 3 alert and "SEL AUTO" message is generated. Data may be entered for a single future control option during execution of the current option.

When the START TIME entered for the future option equals current time, the "*" in the FUT column is blanked and "*" displayed in CUR column. If the previous control option is active, it is deselected (no "*"). If a future option has been selected and then data are changed prior to the future start time via keyboard inputs, the future option will be deselected (no "*"), and CANCEL (CNCL) will be automatically selected. The crew must repeat selection of the desired future option.

The three control options are terminated/inhibited by: (a) selection of MNVR (item 27) on the MM 202 ORBIT MNVR EXEC display (which maneuvers to the specified burn attitude); (b) selection of LVLH or MAN pushbutton (pb); (c) moving an RHC out of detent; (d) selection of the CANCEL option, or (e) OMS/RCS ignition. Providing that CANCEL has not been executed, a control option is reinitiated by: (a) exiting MM 202 (ORBIT MNVR EXEC) back to MM 201 (which is the only legal transition) or (b) selecting the AUTO DAP pb.

- e. CANCEL (item 21) deselects both current and future control options and initiates inertial attitude hold at the current attitude. The display is initialized with item 21 selected. When in DAP AUTO and CNCL is selected, attitude errors are displayed with respect to the current attitude when the CNCL option was executed. This attitude reference is maintained in a subsequent selection of a MAN MNVR and return to AUTO DAP. Reselection of the CNCL option zeroes these attitude errors. Then errors are displayed with respect to the current attitude regardless of DAP configuration.

Even in MM 202, selecting LVLH on the orbital DAP control panel reinitiates the LVLH processing done by UNIV PTG processor, but does not reinitiate any other AUTO MNVR mode.

After a transition from MM 201 to MM 202 or OPS 8 and a subsequent transition back to MM 201, the item select status that existed prior to cancellation is shown on the UNIV PTG display. The UNIV PTG display is initialized only when OPS 2 is entered from an OPS other than OPS 8.

Selecting the LVLH attitude mode via pushbutton inhibits the cyclic processing of the selected AUTO attitude option (item 18-20) until the LVLH attitude mode is deselected.

3.1.1.2 Attitude Monitor

Select ERR TOT (Item 23) or ERR DAP (Item 24) at crew option. DAP errors show effects of attitude deadbanding (ATT DB), and allow crew to anticipate RCS firings to maintain attitude; TOT errors allow monitoring how far the Orbiter is out of a desired attitude (e.g., a track attitude, such as used to maintain V-BAR). When the ADI error needles are displaying TOTAL ERROR, they display DAP ERROR by simply selecting ITEM 24 on UNIV PTG. No cycling of the DAP is required to make the ITEM 24 take effect.

3.1.1.3 Enhanced Universal Pointing

For software release OI 12 with the new general purpose computers (GPC's), there will be a major upgrade of UP/DAP capabilities. Their applications to RNDZ are as yet undefined, but are likely to be extensive. The following description is intended for future users so they will have a proper understanding of Orbiter capabilities after the UP/DAP modification. Closer to the operational date of this new capability, this entire section will be replaced with a new section.

The UP upgrade is via CR 79879. It is a companion to CR 79862.

In the upgraded UP, up to 25 future AUTO MNVR's will be contained in a "maneuver table" (each entry can be loaded, edited, or canceled). Each maneuver will have its own ID number, start time, and DAP/jet selection (currently only a single "future option" can be stored, and DAP/jet select can be made from pb's only for the maneuver (designated "MNVR"). A second DAP load and jet selection are entered in the maneuver definition to specify the configuration to be used when the the desired attitude has been reached or tracking hold has been established (designated "HOLD"). For the ROT option, which never "ends," no such entry is made. If a current maneuver is canceled, the DAP/jet select reverts to those last loaded prior to the beginning of that current maneuver.

The future maneuver stack can be enabled or inhibited by item entry. As entries are made/edited in this table, it is automatically put in chronological order. In another upgrade, DAP's can be called up by number (e.g., DAP "ALL") rather than making individual entries on SPEC 20. These future AUTO maneuver's will be loadable by I-load (activated upon entry into OPS 2 from any legal OPS except OPS 8), uplink, as well as by keyboard (at present, only keyboard loads are possible); they can be downlisted (one maneuver per UP cycle) for verification.

Once a maneuver becomes "current", it can only be manipulated in certain restricted ways. It can only be canceled by crew input, not by uplink.

Another major upgrade involves maneuver options. A "tracking/rotation" (TRK/ROT) option is added, which allows rotation (at a constant rate) to be performed about the pointing vector during TRK operations. LVLH reference frame becomes available (in addition to inertial frame as currently) for output angles (attitude and attitude error and rates) and for attitude/

3.1.2 Rotational Hand Controller and Translational Hand Controller

The rotational hand controller (RHC) and THC (aft station, panels A7U and A8) are used to provide input commands to the DAP, which then (depending on DAP configuration) outputs appropriate RCS jet fire commands. The THC outputs single commands when deflected; the RHC has a soft stop and hard stop feature that outputs separate signals which can be interpreted differently depending on DAP mode (fig. 3-2).

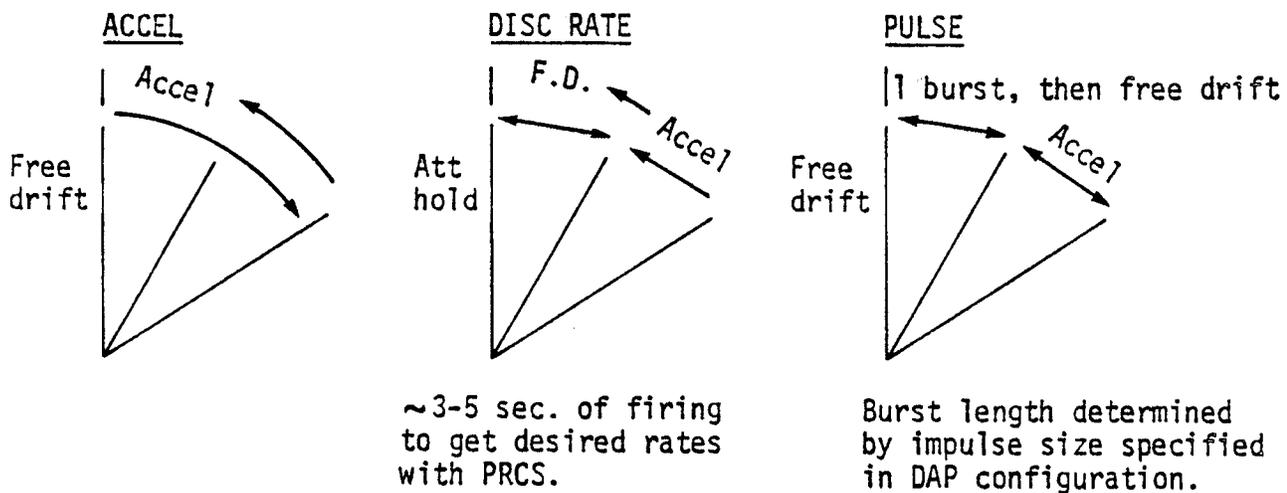


Figure 3-2.- RHC soft/hard stop logic.

Detailed descriptions of the functioning of the RHC and THC can be found in the Attitude/Pointing Flight Procedures Handbook and the Controllers Workbook.

Visualizing THC/RHC control modes in the two aft sense options can be facilitated by imagining an Orbiter being grasped by the hand on the RHC/THC, where the gross deflections of the RHC/THC are duplicated in same-sense motions of the actual Orbiter. The "sense" is down the crewmember's arm: -X has the Orbiter tail pointing down the arm and its top up; -Z has the Orbiter top pointing down the arm with its nose up. This is directly analogous to the forward RHC/THC +X sense mode.

3.1.3 SENSE Switch Options

The SENSE switch (panel A6U) allows the RHC and THC to command relative to the current control axis, either -X or -Z depending on whether the crewmember (at the aft crew station) is viewing through the payload bay PLB windows or the overhead windows (fig. 3-3). The vehicle motions induced by RHC and THC deflections are relative to the desired control axis as selected by the SENSE switch position (figs. 3-4A and 3-4B).

For RNDZ/PROX OPS applications, the proper setting of this switch is -Z. This is true especially for post-Ti through grapple, and for separation as well. The crew may also select this at any other time. The only proper use of -X sense is as a backup to the forward THC for translation, particularly for burn completion.

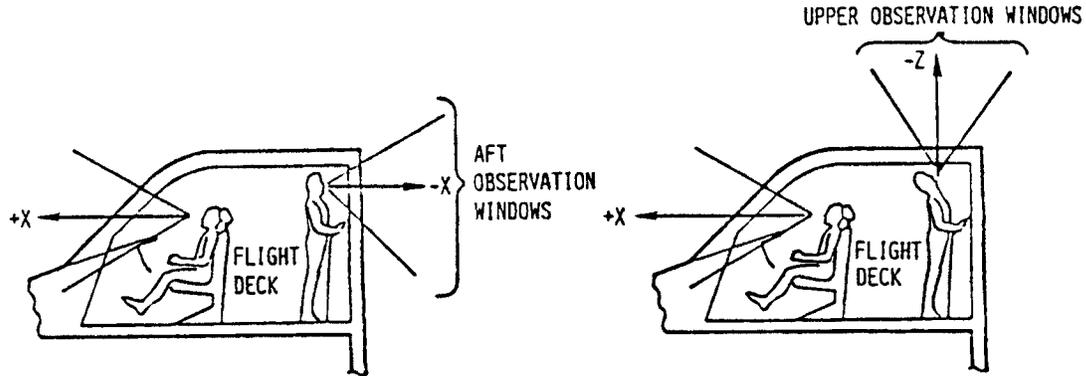
3.1.4 See page 3-12

3.1.5 "FWD Tank Constraint" issues [written 5/18/1988]

A significant consideration in Orbiter attitude control is the DAP implementation of old constraints on the maximum number of forward RCS jets which can fire simultaneously. Too high a number was once thought to create the possibility of helium ingestion in the FRCS tanks, so a high limit of 3 FRCS jets was apparently implemented in FSW. Later, flight experience and hardware analysis relaxed this concern, and so CR 69781 was approved to remove this constraint. However, this limit's implementation in FSW and in simulators was clouded in the return-to-flight era (1987-1988) since proper paper trails could not be followed. Close coordination with DM43 specialists is required for an up-to-date appreciation of the real status of this issue. Analysis of FSW code was incomplete as of publication date.

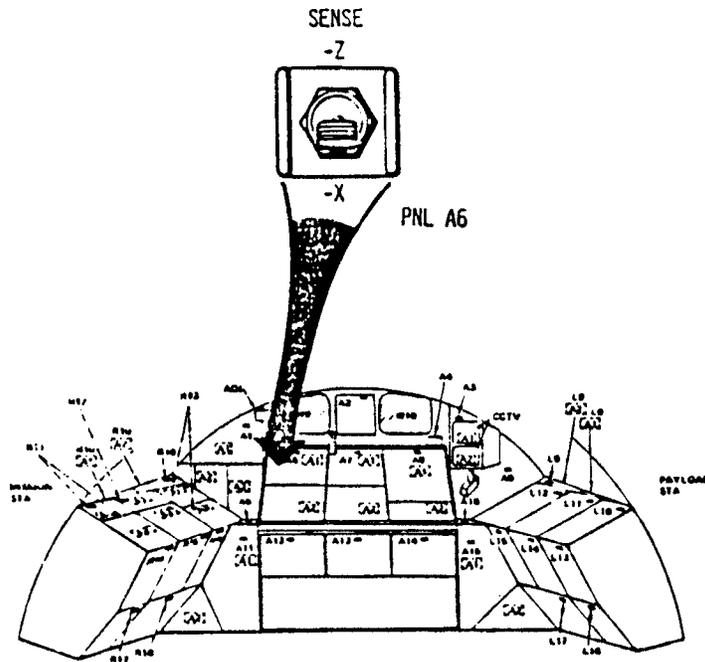
Impact on proximity operations procedures (particularly separation sequences from large payloads) can be significant and surprising. For example, while in low Z mode (NORM-NORM-NORM) a prolonged -Z translation (2 +X jets and 2 -X jets) can create a pitch down which soon exceeds the deadband and thus commands a pitch up using two forward down-firing jets. To satisfy the constraint, the DAP cuts off one of the -X jets for the duration of this pitch up firing (several seconds), but leaves the two +X jets on, causing an X-axis imbalance and a consequent +X small translation. So instead of a nearly pure -Z translation (as commanded) this THC input results in a departure vector tilted forward about 30 degrees, possibly leading to RMS/PL contact. NOTE: Performing such a separation in PULSE mode avoids this difficulty.

AFT STATION CONTROL



- TWO SETS OF WINDOWS-AFT (-X) AND OVERHEAD (-Z)
- ONE SET OF AFT STATION CONTROLS (RHC & THC)
- MUST ESTABLISH A VISUAL CONTROL REFERENCE BASED ON THE LINE OF SIGHT
- DONE WITH THE AFT SENSE SWITCH

AFT SENSE SWITCH



-Z SELECTS THE CONTROLLER & ADI REFERENCE ABOUT THE -Z AXIS, IE, OVERHEAD LINE-OF-SIGHT REFERENCE.

-X SELECTS THE CONTROLLER & ADI REFERENCE ABOUT THE -X AXIS, IE, AFT LINE-OF-SIGHT REFERENCE.

AFT STATION

Figure 3-3.- Aft station control, sense switch.

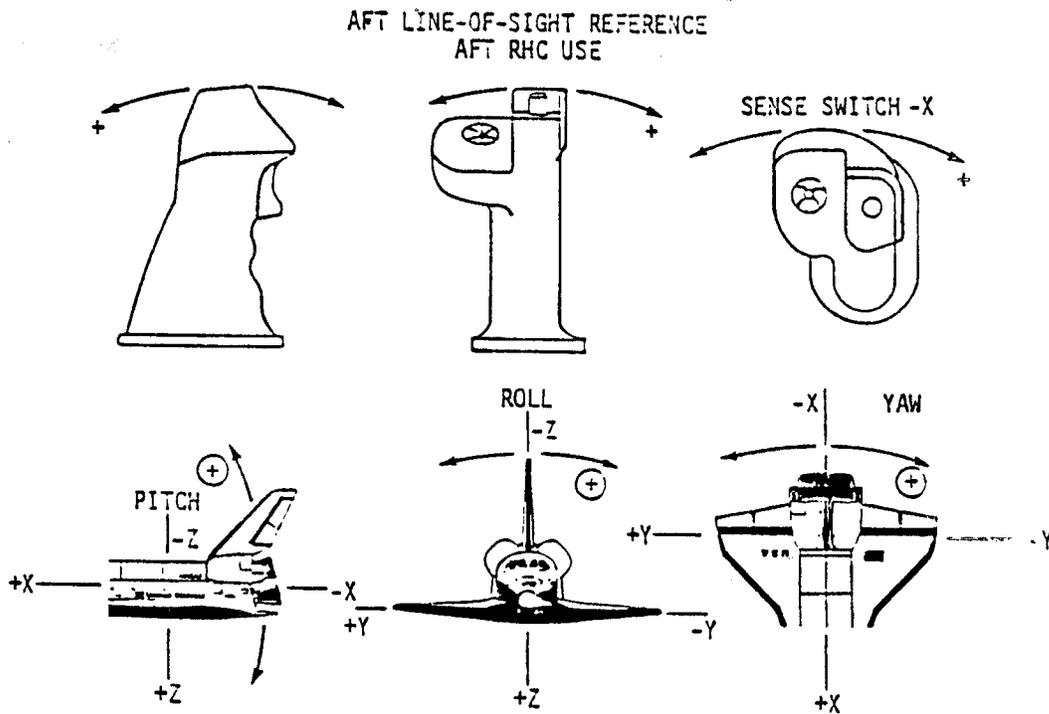


Figure 3-4A.- Aft and overhead line-of sight references, aft RHC use.

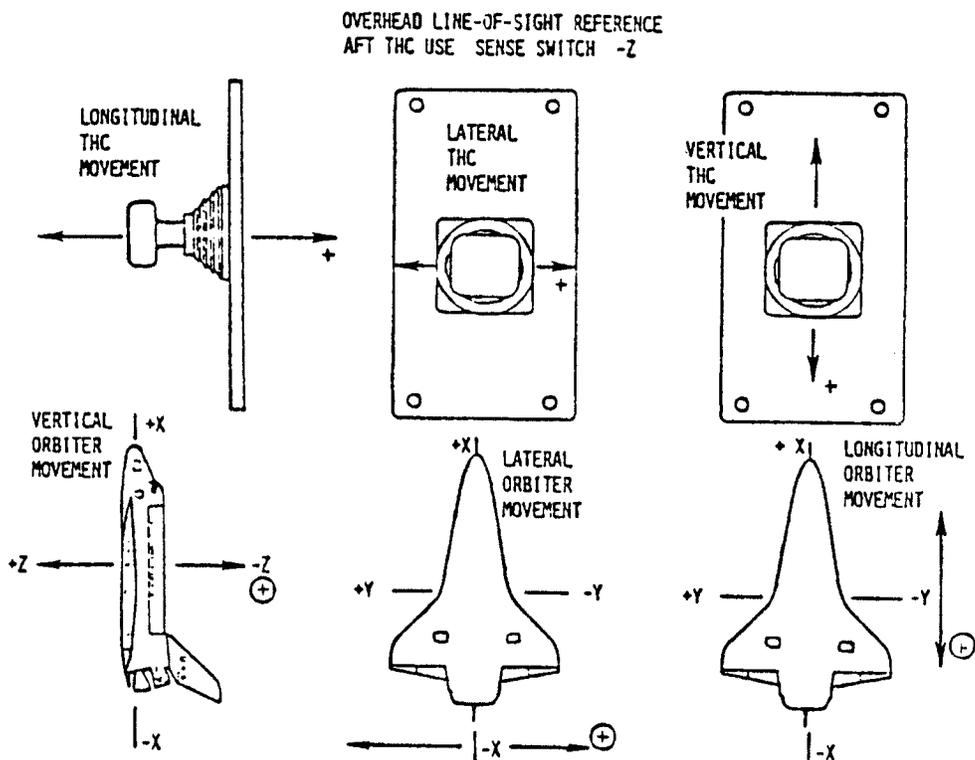
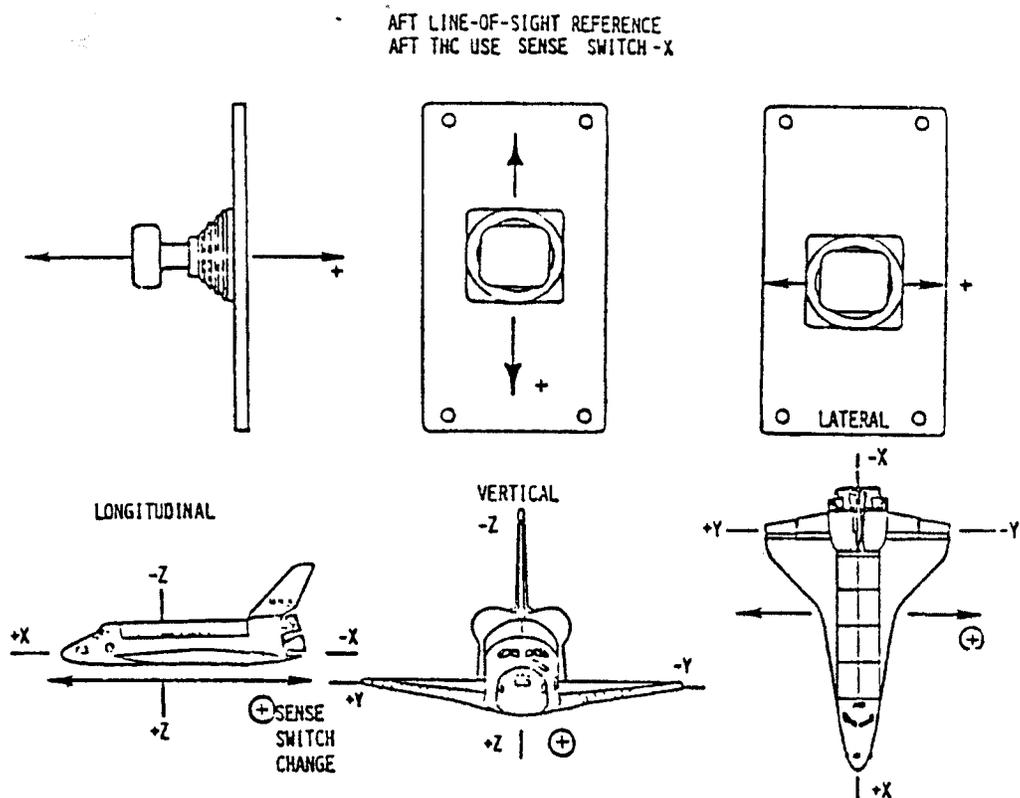


Figure 3-4B.- Aft and overhead line of sight references, aft THC use.

3.1.4 Attitude Direction Indicator (ADI)

The ADI is a crew-observed hardware instrument that provides indications of the Orbiter pitch, yaw, and roll attitude via a gimballed ball (fig. 3-5).

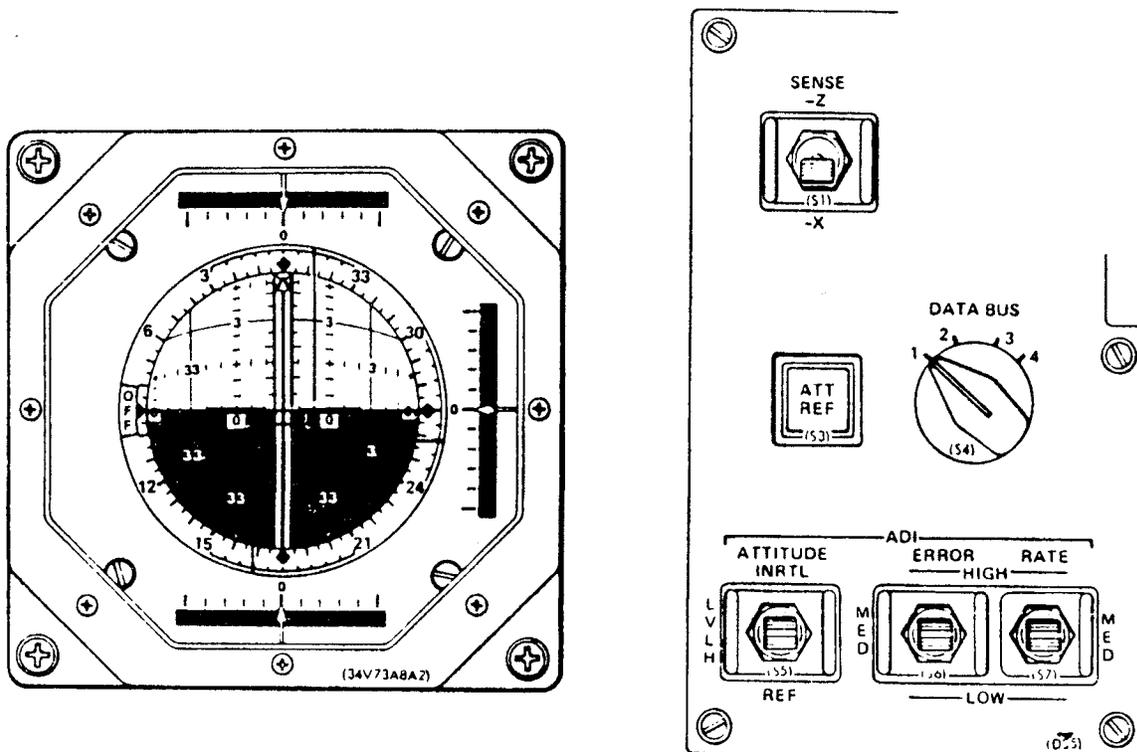


Figure 3-5.- Aft station ADI displays and controls.

Attitude errors are shown by three metered position needles; attitude rates are indicated by three metered position pointers. Top is roll, right side is pitch, bottom is yaw. The scale for each of the three ADI's is controlled by the ADI scale switches; the aft switch is on panel A6U. Each ADI can be set to an error level of high, medium, or low (10, 5, or 1, with the units "degrees" (error) or "deg/s" (error rate)); RNDZ procedures call for selection of "MED." When change from AUTO to MAN is made on the DAP, the ADI error needles will reflect the desired tracking or MNVR attitude loaded on UNIV PTG. See section 3.1.1.2 for the effect of ERR TOT/DAP selection.

The ADI error needles change when the DAP is moded to LVLH. The error needles go to zero. When the LVLH pushbutton is pressed, the current Orbiter attitude is defined as the reference LVLH ADI attitude, making the attitude error zero.

The ADI attitude switch selects the ADI reference frame desired for display on the ADI. The switch selections are INRTL, LVLH, and REF. The INRTL and REF reference frames are defined by I-loaded RELMAT's (inertial system is M50). The crew can also set up their present attitude as the REF reference frame for future reference by pressing the ATT REF pb on panel A6U.

The SENSE switch allows the aft ADI angles to indicate the orientation of either a -X sense axis system or a -Z sense axis system depending on whether the crewmember is viewing through the payload bay (-X) windows or the overhead (-Z) window. These sense-axes systems (-X, -Z) are fixed in the body, and the ADI displays the pitch, yaw, and roll of the sense system axes with respect to the ADI reference frame as defined by the RELMAT. More details on the use of the SENSE switch are in section 3.1.3.

A more detailed discussion of the ADI can be found in the Attitude/Pointing Flight Procedures Handbook.

3.2 DIGITAL AUTO PILOT (DAP)

The Orbiter DAP is controlled by the crew via the DAP CONFIG (SPEC 20) display and the DAP pushbuttons. Different values of attitude/rate deadbands (DB's) and translation/rotation pulse sizes are selected during different mission phases in order to best accommodate the often-conflicting requirements for MNVR timelines, pointing accuracy, and propellant economy.

In practical terms for this application, the major differences between DAP A and DAP B are pulse size for the PROX OPS DAP's and pulse plus rotation maneuver size in the RNDZ DAP's. While in the RNDZ DAP's, when DAP B is called for, it is because a higher maneuver rate is required. That is, DAP A will be used for attitude control with vernier jets and DAP B will be used for attitude maneuver with normal jets. DAP A also has a translational pulse size that is twice as large as DAP B.

3.2.1 DAP Management

The first requirement for RNDZ-specific DAP values is to minimize differences between the standard A1/B1 values and the values for RNDZ (called A9/B6) and for PROX OPS (called A10/B7). Specific differences are justified by phase-unique and payload-unique features (e.g., see section 4.1.66)

For translation pulse, DAP A is traditionally larger than DAP B. For RNDZ, they are 0.1 and 0.05 ft/s; for PROX OPS, they are 0.05 and 0.01 ft/s (the 0.01 value results in the smallest possible pulse size, 80 milliseconds).

For rotation during RNDZ, there is the need for occasional fast maneuvers. The DAP B has a 0.5 deg/s NORM discrete rate. During PROX OPS and most attitude maneuvers during the RNDZ, a slow rotation rate (0.2 deg/s) is used for both DAP's A and B, both NORM and VERN. Occasionally there is a need to maneuver at the higher 0.5 deg/s rate (e.g., post-Ti if radar fails, the crew needs to get back to -Z target track fast to get STRK NAV marks).

For DB's, the large values for A1/B1 are reduced to values which have proven suitable in flight and in ground simulations. For RNDZ and PROX OPS, the values are 2° (NORM) and 1° (VERN) for both DAP's A and B (the standard values are 5/1 and 3/1). The values of these DAP's are shown in figure 3-6.

During the RNDZ, in general DAP A is selected. DAP B is used for higher rotational precision (such as during COAS marks), finer translational control (V-BAR approach), or higher attitude rates (such as during maneuver to/from Ti burn attitude). Jet selection is nominally VERN, with NORM for translation or 0.5 deg/s maneuvers; AUTO is nominally selected, to allow UP control for TGT track or for maneuvering to attitude; MAN is selected to execute burns or for INRTL ATT hold; LVLH is seldom used.

During the PROX OPS phase, in general DAP B is selected for stable periods or where fine translational control is required. DAP A is selected during dynamic operations because of the greater control authority defined by RCS pulse/discrete values. The VERN/NORM and AUTO/MAN selections are the same as during the RNDZ phase. See section 5.1.1.1 for operational details.

For heavy payloads such as Long Duration Exposure Facility (LDEF), the CNTL ACCEL values are set to zero during rendezvous and PROX OPS.

Note: The upper and lower limits on selectable DB parameters are as follows for NORM (VERN) jets:

attitude hold (deg)	0.10 (0.01)	to 40 (40)
discrete rate (deg/s)	0.05 (0.002)	to 2 (1)
rot pulse (deg/s)	0.04 (0.001)	to 1 (0.5)
trans pulse (ft/s)	0.01	to 5

DAP	RENDEZVOUS		PROX OPS		SPEC 20 ITEM NO	
	A9	B6	A10	B7	A	B
<u>TRANSLATION</u>						
PULSE FT/SEC	0.10	0.05	0.05	.01	1	15
<u>ROTATION</u>						
DISC RT NORM	0.200	0.500	0.200	0.200	2	16
VERN	0.200	0.200	0.200	0.200	3	17
<u>PULSE</u>						
NORM	0.10	0.04	0.10	0.04	4	18
VERN	0.010	0.002	0.010	0.002	5	19
<u>DEADBAND</u>						
ATT NORM	2.00	2.00	2.00	2.00	8	22
VERN	1.000	1.000	1.000	1.000	9	23
<u>RATE</u>						
NORM	0.20	0.20	0.20	0.20	10	24
VERN	.020	.020	.020	.020	11	25

Figure 3-6.- DAP configurations for rendezvous/PROX OPS.

The tail-only/nose-only option is not currently planned for use. However, multiple jet failures, vernier reaction control system (VRCS) failures, or forward prop being critically low, may lead to such a configuration.

3.2.2 DAP Configuration (SPEC 20)

DAP CONFIG (fig. 3-7) is a GNC specialist function available in OPS 2. Among other things, it allows the crew to specify the size of attitude and rate DB's and the magnitude of discrete/pulse RCS attitude/translation maneuver's.

Two sets of numbers are maintained (designated "A" and "B") and can be readily changed during a flight. In practice, the primary difference between DAP A and DAP B will be the translation pulse size, with DAP A having the larger. Selection of "A" and "B" is via console pb (section 3.2.3.).

The significance of the DAP A(B) item entries is as follows:

- 1(15) is PULSE, a means of specifying the desired ΔV (ft/s) resulting from a single THC deflection. Multiple deflections are additive.

XXXX/O20/		DAP	CONFIG	XX X	DDD/HH:MM:SS	DDD/HH:MM:SS
TRANSLATION			A	B		
PULSE		1	<u>X.XX</u>	15	<u>X.XX</u>	
ROTATION						
DISC RATE	NORM	2	<u>X.XXX</u>	16	<u>X.XXX</u>	
	VERN	3	<u>X.XXX</u>	17	<u>X.XXX</u>	
PULSE	NORM	4	<u>X.XX</u>	18	<u>X.XX</u>	INERTIAS
	VERN	5	<u>X.XXX</u>	19	<u>X.XXX</u>	29 IX <u>X.XXX</u>
COMP	NORM	6	<u>.XX</u>	20	<u>.XX</u>	30 IY <u>X.XXX</u>
	VERN	7	<u>.XXX</u>	21	<u>.XXX</u>	31 IZ <u>X.XXX</u>
DEADBAND						
ATT	NORM	8	<u>XX.XX</u>	22	<u>XX.XX</u>	
	VERN	9	<u>XX.XXX</u>	23	<u>XX.XXX</u>	
RATE	NORM	10	<u>X.XX</u>	24	<u>X.XX</u>	
	VERN	11	<u>.XXX</u>	25	<u>.XXX</u>	
JET OPT	P	12	<u>X</u>	26	<u>X</u>	
	Y	13	<u>X</u>	27	<u>X</u>	
CNTL ACCEL		14	<u>X</u>	28	<u>X</u>	

(XX)

Figure 3-7.- The DAP CONFIG (SPEC 20) display.

- 2(16) and 3(17) are DISC RATE for primary and vernier jets respectively; they are used to specify the desired rotational rate (deg/sec) to be achieved for a discrete rate manual command (MAN or MAN LVLH), or for an AUTO MNVR, AUTO MNVR to TRK attitude, and for AUTO ROT.
- 4(18)/5(19) are PULSE, or the primary/vernier values used to specify the rotational rate (deg/s) resulting from each single manual RHC pulse command. Multiple deflections are additive.
- 6(20)/7(21) are COMP, used to specify the threshold ROT rate (deg/s) for a given axis resulting from a rate command about another axis. When that threshold is reached, the DAP will command jets to reduce the rate. Note that an entry of zero implies that the DAP will attempt to compensate for all cross-coupling, but it actually disables ROT compensation. Minimum entry to enable ROT COMP is 0.113 deg/s primary RCS (PRCS) and 0.003 deg/s (VRCS).

At the present time, ROT COMP is not used nominally, due to high fuel use and incompatibility with any DAP mode other than free drift. Instead, normal DAP attitude hold is used to minimize undesired cross-coupling effects.

- 8(22)/9(23) is attitude (ATT), used to specify the attitude DB's (degrees) for primary/vernier jets.
- 10(24)/11(25) is RATE, used to specify the rate DB's (deg/s) for primary/vernier jets.

In addition, various jet options can be selected (for primary jets only). The options are "normal" (1), "nose only" (2), and "tail only" (3). For pitch, one can choose the option with item 12(26); for yaw, the choice of option is via item 13(27); there is no option for roll, since it is always tail only, PRCS. Translations are always "normal"; control is always "normal" anytime VRCS is selected.

3.2.3 DAP Pushbuttons

The DAP pb's on panel A6 (fig. 3-8) allow selection of various control modes in the Orbiter response to RHC/THC input commands from a crewmember or AUTO commands from the DAP. An identical set of pb's is on panel C3. Note that the specific DAP lights illuminated on the forward and aft panels will not necessarily be identical. In particular, since the forward RPY indicators are always in the +X sense while the aft RPY indicators can be in -X sense or -Z sense, any mixed configuration (e.g., DISC-PULSE-DISC) may not look the same on both panels. Thought must be given to which axis in which sense is being specified by each light.

The on-orbit DAP functions are DAP A or B with AUTO, MAN, or LVLH rotation modes selected, and a choice of NORM or VERN jets. There is also a choice of DISC RATE, ACCEL, or PULSE manual (MAN) ROT submodes selectable by axis. With NORM jets selected, the following translational submodes are available: PULSE and NORM (ACCEL) in all axes, HIGH Z (high ACCEL), NORM Z, and LOW Z (upfiring jets inhibited always) for +Z translations.

DAP's A and B each represent different sets of control parameters for the DAP. These parameters can be seen on the DAP CONFIG specialist function (SPEC 20), and can also be changed through keyboard item entries on this display (section 3.2.2). These changes are invoked after the item execution, if the parameter changed is applicable to the currently selected DAP (A or B and NORM or VERN). The following modes and submodes are available for DAP on-orbit operation.

3.2.3.1 AUTO/MAN Selection

AUTO enables execution by the DAP of AUTO maneuvers commanded by use of the UNIV PTG display (section 3.1.1); MAN enables execution of the selected ROT submodes manually commanded through the RHC.

Note: Any input from an RHC causes automatic downmode from AUTO to MAN.

3.2.3.2 LVLH

With DISC RATE selected in all three axes and with the LVLH mode selected, the LVLH attitude that existed at the time of selection of LVLH will be held fixed within the LVLH frame until changed by use of the RHC. The RHC can be used with LVLH selected to change the LVLH attitude. While out of detent, the Orbiter maneuvers at DISC RATE. When the RHC returns to detent in any axis, the LVLH attitude in that axis is held fixed again. This mode would be used manually for precise PROX OPS attitude control in the near vicinity of a target, an example being flyaround (section 5.2) of an LVLH-stabilized target.

Note: For LVLH mode to work, at least one ADI must be in LVLH mode. Otherwise, required computations will not be performed and resulting attitude will be unpredictable.

3.2.3.3 NORM/VERN Jet Select

Primary RCS (PRCS or NORM) and vernier RCS (VRCS or VERN) jets can be used for attitude hold and maneuvers. NORM jets must be selected for translation maneuvers. With primaries selected, there is a choice through the DAP CONFIG display (SPEC 20) via the JET OPT for tail jets only, or nose jets only to be used for pitch/yaw control (in VRCS rotation is always a combined tail/nose function).

3.2.3.4 Translation Submodes (NORM Jets Required; MAN, MAN LVLH, and AUTO)

- PULSE X, Y, or Z - With this submode selected, each deflection of the THC will result in a change in velocity of the magnitude specified for TRANSLATION PULSE on the DAP CONFIG display for the selected DAP (A or B) in the axis and direction (+ or -) of the THC deflection.

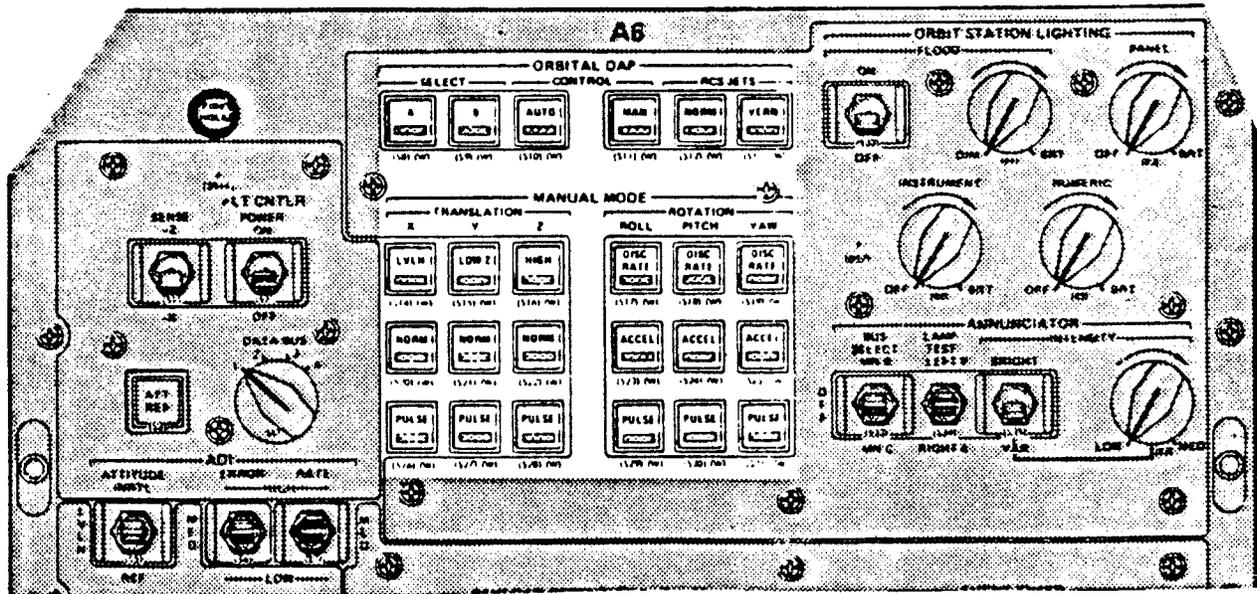


Figure 3-8.- Panel A6.

- NORM, X, Y, or Z - With one of these submodes selected, continuous acceleration will occur at whatever level is available with the commanded jets for the axis and direction (+ or -) of the THC deflection as long as the THC is deflected.
- HIGH Z - An ACCEL submode that is available for +Z translation only. Selection of this submode fires more jets than are fired for the NORM =Z command. This option is currently not used.
- LOW Z - Low Z is a submode that takes advantage of some +Z thrust components that exist for both the +X and -X translational jets. To get the +Z translation, the +X and -X translational jets are fired simultaneously so that the jets nearly cancel the X components of each other and combine the small +Z components. The result is a small +Z velocity change at about 10 times the normal prop usage. See section 3.2.4 for applications. The RCS plume overpressures for low Z MODE versus NORMAL Z MODE are shown in figure 3-9. Low Z translations also affect pitch and roll, since upfiring jets are inhibited. This results in significant -Z translational cross-coupling (see section 6.2.1), but reduces the duty cycle for attitude maintenance.

3.2.3.5 Manual Rotational Submodes

- DISC RATE - ROLL, PITCH, or YAW - With the DAP mode MAN and the submode DISC RATE, when the RHC is deflected out of the detent (but not past the soft stop) in an axis, jets are fired until an angular rate is achieved in that axis equal to DISC RATE specified in the DAP CONFIG display for the selected DAP (A or B) and selected jet option (NORM or VERN). When the rate is achieved, the jets are turned off until the RHC is returned to detent in that axis unless the jets are momentarily required to maintain attitude or rates within the DB's. When the RHC is returned to detent in an axis, the attitude in that axis is snapshotted and jets are fired to stop the rate in that axis and to begin holding the snapshotted attitude.

If the RHC is deflected beyond the soft stop while in DISC RATE (and any DAP mode/submode), jets are fired continuously, giving a constant angular acceleration (in the axis and sense of the RHC deflection) until the RHC is backed out of the soft stop, at which time the jets are turned off. When the RHC is returned to detent, the attitude is snapshotted and jets are turned on to stop the angular rates and initiate hold about the snapshotted attitude. In effect, this provides an ACCEL mode if the RHC is deflected past the soft stop, and a free drift mode when returning the RHC from the soft stop while between the soft stop and detent. See figure 3-2 in section 3.1.2.

- ACCEL - ROLL, PITCH, or YAW - When the DAP mode is MAN/ACCEL and the RHC is deflected out of detent, a fixed number of jets is fired to provide constant angular acceleration as long as the RHC is out of detent in the axis and sense of the deflection. When the RHC is returned to detent, the jets are turned off, but the angular rates continue. The result is a free mode since the attitude is uncontrolled when the RHC is in detent (free drift at the existing angular rates).
- PULSE - ROLL, PITCH, or YAW - When the DAP mode is MAN/PULSE and the RHC is deflected out of detent, jets are fired just long enough to achieve the angular rate change specified on the DAP CONFIG display for rotation pulse for the axis and sense of the RHC deflection. PULSE is also a free drift mode.

3.2.3.6 Applications

These DAP options can be used as follows:

For free drift, select MAN PLS/PLS/PLS. See section 5.4.1.5 for example.

For inertial attitude hold, select MAN DISC/DISC/DISC. See section 4.1.61 for example.

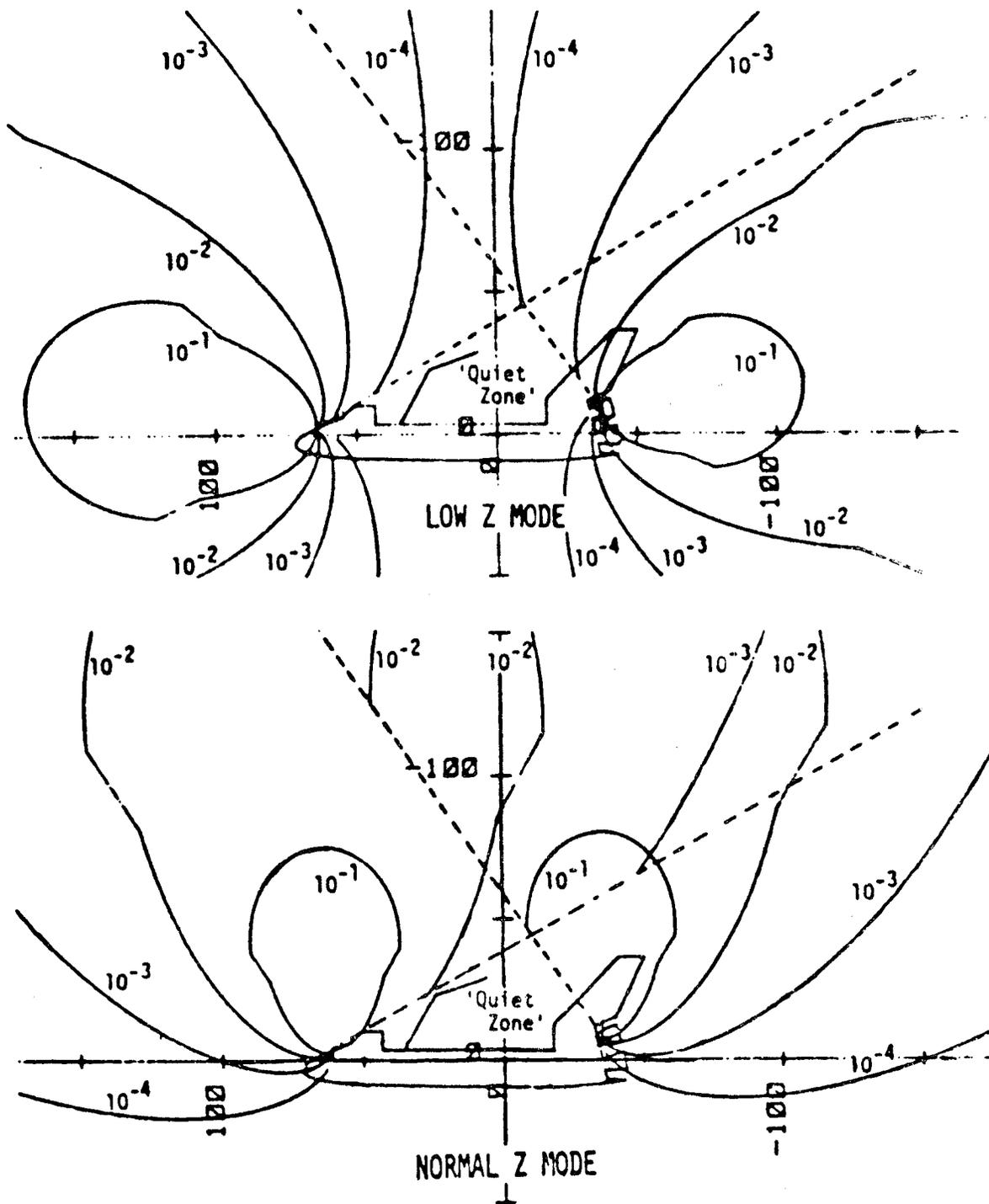


Figure 3-9.- RCS plume overpressure for LOW Z and NORMAL Z mode (lb/ft²).

3.2.4 Low Z Operations

3.2.4.1 Plume Impingement (PI) Issues

Within about 1000 feet, attention should be given to effects of RCS jet firings. One effect is contamination by combustion products and/or unburned propellants; the other effect is disturbance of the target attitude and position by the plume overpressure. Choice of low Z mode (and the expense associated with it) is made based on those factors. Due to shadowing by Orbiter structure, a target close above the PLB may be out of the RCS plumes, and normal Z mode may be resumed while the target remains in this zone (see fig. 3-9). A full discussion of propellant plume issues is found in section 3.8.2.

3.2.4.2 Low Z Operations

The low Z DAP mode (mentioned in section 3.2.3.4 and described and illustrated in section 5.3.1.2) was designed to minimize both types of RCS PI on targets. A given technique that offers acceptable PI effects in one of these areas may or may not satisfy acceptable limits in the other. Low Z does minimize PI effects at a direct cost of about 10-12 times the NORM Z fuel usage. However, the penalty of low Z operations is not limited to this increase in fuel usage. Due to cross-coupling effects (see section 6.2.1) resulting from braking, -X translations, and VRCS attitude control, only about one-half of a given commanded braking pulse is actually received. Further, there is a tendency for rapid buildup of a closing rate during stationkeeping or precisely scheduled range/range-rate V-BAR approaches, due in large part to cross-coupling from +/- Y translations. These rates can reach 0.2 ft/s or more, requiring more braking, resulting in a vicious circle. These effects can be particularly serious when trying to establish V-BAR stationkeeping following the manual phase of the RNDZ, either while in low Z mode, or especially if the low Z mode is selected prematurely. Prop usage rates of 8 to 12 pounds per minute are not unheard of (4-6 pounds per minute is more common), much higher than the 1 to 1.5 pounds per minute for normal stationkeeping. Usage can be controlled to 2 pounds per minute or less by taking great care in stabilizing on the V-BAR at the precise position required for the desired range (see PROX OPS cue card, section 4.3.5) prior to selecting low Z. Stabilizing on the V-BAR following a RNDZ in the low Z mode is not recommended.

Flight experience has revealed several common mistakes involving use of low Z mode. First, during approach, some crews have exited low Z mode using loss of radar lock (80 to 90 feet) as the cue, when in fact the target is not yet in the Orbiter body "shadow" (less than 50 to 60 feet range, directly over the PLB). Second, during PROX OPS, the low Z mode select pb may be pushed repeatedly, leaving the DAP back in low Z when the pilot believed it was in NORM Z. Great care must be exercised since propellant consumption can be critical and, under marginal conditions, be cause for calling a PROX OPS BREAKOUT if usage is excessive.

3.3 RENDEZVOUS/PROX OPS SENSORS

Prior to the day of RNDZ, on-board NAV sensors are not required since the ground is targeting all MNVR's and the relative separation of the Orbiter and TGT is sufficiently large. On the day of RNDZ, with no functioning NAV sensors, flight rules specify to proceed to Ti (this is done in the hope of acquiring sensor data or visual acquisition) and then breakout post-Ti if no acquisition.

3.3.1 Star Tracker

The two star trackers (STRK or S TRK) (-Y and -Z) are nominally used to take sightings on stars so as to align the IMU's. They also can track TGT satellites and provide angular data for use in onboard relative NAV. Their nominal TGT brightness range is from +3 to -8 stellar magnitude (brightness is monitored in the MCC, but is not displayed on board).

During RNDZ operations, the purpose of the star trackers is to provide Orbiter body-axis measurements of the TGT LOS. This is called "target track mode."

Lighting constraints limit STRK operations to conditions when the TGT is illuminated. For a standard RNDZ profile from behind and below, this occurs during the period between orbital noon and sunset. This period could be extended if the TGT has appropriate artificial lighting systems. Such extensions should help reduce dispersions in a radar fail case.

3.3.1.1 Control Switches

The STRK control switches are found on panel 06 (fig. 3-10) and involve power and door control. Door position is shown on talkbacks.

3.3.1.2 Capabilities

Each STRK has a $10^\circ \times 10^\circ$ square FOV. There is a bright object sensor (BOS) which closes a protective shutter (or door) over the STRK optics when the STRK is pointing within 16° to 19° of the sunlit Earth limb, or $30'$ of the Sun or $8'$ of any other magnitude -12 object, (e.g., the Moon).

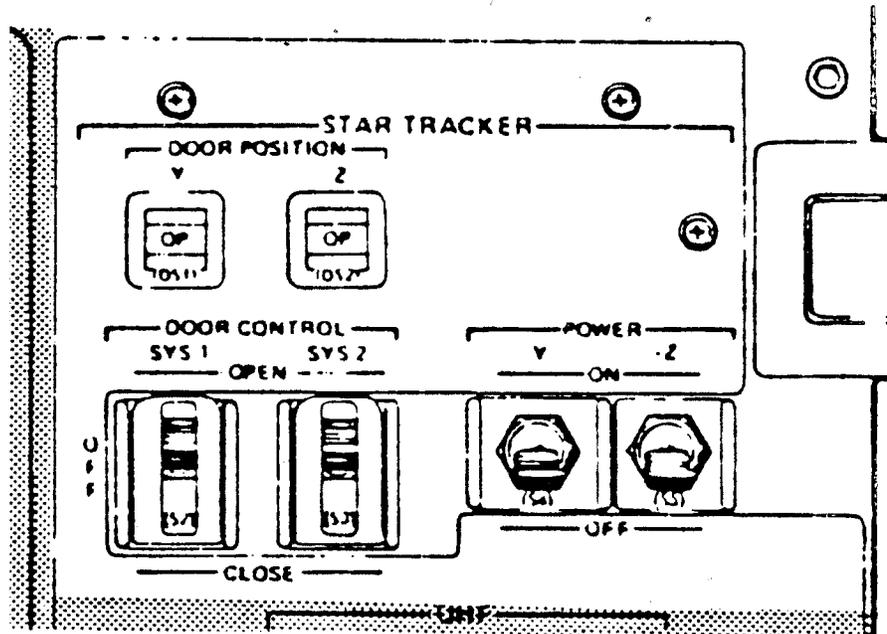


Figure 3-10.- Panel 06.

On STS-8, STRK tests were conducted near the sunlit Earth limb. The lowest +3 magnitude star angle above horizon at acquisition was 13° , when the boresight angle was 12° . Background noise and false tracks increased dramatically after this last track. Lower angles might be possible by offsetting the boresight to above the target, or by use of STRK thresholding (ITEM 13, 14) for brighter TGT's (this option is not currently utilized). Angles below 5° - 7° are considered impossible due to the horizon in the FOV. All baselined RNDZ profiles involve targets 20° - 30° above the limb.

When the shutter is closed, the crew gets a closed indication, but cannot tell if it was due to the TGT suppress (TS) or BOS. The hardware fix for this included raising the TS spec limit from -8 magnitude to -12 magnitude, and setting the TS to 1 magnitude brighter than the BOS. The TS range for OV 102 and 099 (-8 magnitude) was 1.7 n. mi. for Solar Maximum Mission (SMM) and 1.4 n. mi. for integrated rendezvous target (IRT), and in fact on STS 41-C the shutter did close during RNDZ at a range of about 1 n. mi.

When commanded to track a TGT, the STRK will center on coordinates provided by NAV and will search a 1° by 1° square. If after 4 seconds the TGT is not acquired, the STRK will search its entire FOV for 20 seconds, at which time a warning message is displayed to the crew if the TGT was not found. If the TGT is acquired, the STRK scans a 12-arc second cruciform track centered on the TGT every 42 milliseconds. The TGT will be tracked until it leaves the FOV or the STRK is commanded to stop.

Once locked on, tracking continues across the FOV at up to 0.2 deg/s with guaranteed accuracy and up to 0.5 deg/s with reduced accuracy.

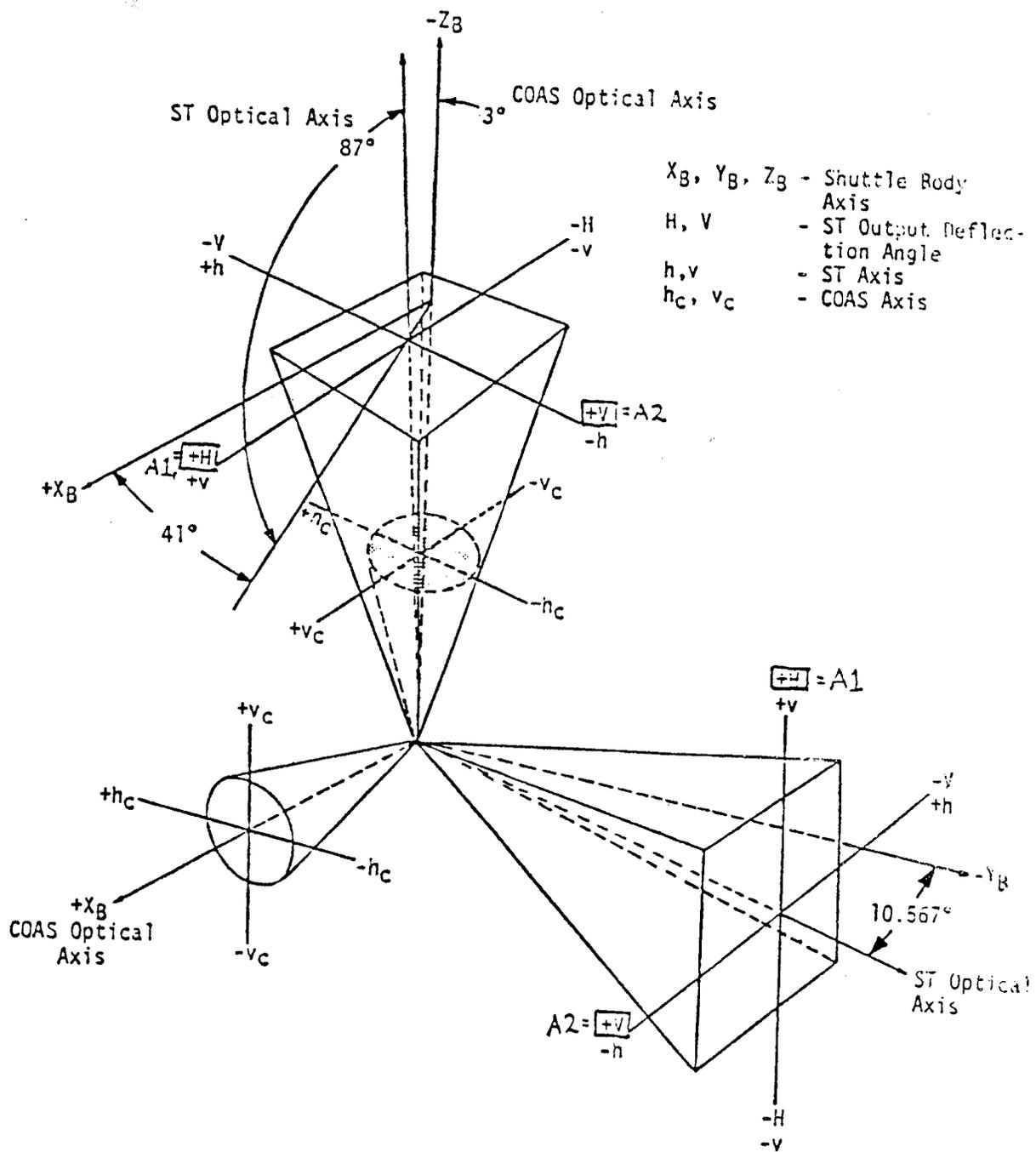


Figure 3-11.- STRK/COAS geometry.

If the TGT passes within $1/4^\circ$ of a bright star, the lock may jump over to that star. The filter will recognize this if it has already processed enough data; the remedial action is to break track and search again.

There is a potential problem with Orbiter-related trash (or ice), which could remain in range for a few REV's. The Y STRK is particularly susceptible to picking up ice shaken loose from a previous water dump.

Star sighting data from the first seven STS missions indicated a total star sighting one-sigma error of 0.016° . This includes STRK bias and noise, as well as IMU structural and resolver errors. The error is far less than the specification value.

3.3.1.3 Lines of sight

The orientation and coordinate systems of the STRK are shown in figure 3-11. The optical axes of the STS are slightly offset from the Orbiter axes. For -Z, it is inclined 3° in a plane rotated 41° from the Orbiter +X axis toward the -Y axis; for -Y, it is in the Orbiter X-Y plane and is rotated 10.567° from the Orbiter -Y axis into the +X axis. For precise Orbiter pointing, therefore, the boresighted trackers are:

	P	Y	OM
-Y	0	280.6	90
-Z	87.7	358	0

Note: For the -Z STRK, for procedural convenience, pointing is usually done along the pure -Z axis, which introduces several degrees offset from the precise boresight. If the combination of SV pointing error and attitude deadbanding is large enough and in the appropriate (or inappropriate, from the Orbiter point of view) direction, the TGT could be out of the FOV. For this reason, small attitude DB's (0.5°) are recommended for target acquisition. Pointing the exact -Z STRK boresight may slightly improve this problem as well.

3.3.2 S TRK/COAS CNTL (SPEC 22)

S TRK/COAS CNTL (fig. 3-12) provides a means of monitoring and controlling STRK operation. It also provides data and controls for COAS operation and calibration, as well as supporting data for IMU alignments.

The STRK can be placed in the TGT track mode via Items 5 and 6 (OPS 2 only). These are mutually exclusive: putting the second STRK in TGT TRK will automatically downmode the first one to TERM/IDLE. For each STRK, TGT TRK and STAR TRK are mutually exclusive; however, one STRK can be in TGT TRK while the other is in STAR TRK. Normally the -Z STRK will be selected. Angle data from the STRK is treated in the REL NAV display (section 3.4).

XXXX/022/	S TRK/COAS CNTL		XX X	DDD/HH:MM:SS	DDD/HH:MM:SS
S TRK CNTL	-Y	-Z	S TABLE	1	2 3
SELF-TEST	1X	2X	TRK ID	XXX	XXX XXX
STAR TRK	3X	4X	Δ MIN	XXX	XXX XXX
TGT TRK	5X	6X	ANG DIF	XXX.X	XXX.X XXX.X
BREAK TRK	7	8	ERR	XX.XX	XX.XX XX.XX
TERM/IDLE	9X	10X	SEL	17X	18X 19X
			S TABLE CLR	20	
S TRK	-Y	-Z	COAS		
REQD ID	11 XXX	12 XXX	REQD ID	21	XXX
TRK ID	XXX	XXX	ΔDEG X		±X.X
S PRES	X	X	Y		±X.X
ΔANG	±X.XX	±X.XX	SIGHT MODE	22X	
THOLD	13 X	14 X	ACCEPT	23	
SHUTTER	XX	XX	CAL MODE	24X	
MAN OP	15X	16x	DES	25X	
STATUS	XXXXXXXXXX	XXXXXXXXXX	POS	+X 26X	-Z 27X
	XXXX	XXXX	ΔBIAS	X.XX	X.XX
			UPDATE	28	29
					(XX)

Figure 3-12.- The S TRK/COAS CNTL display.

The "S PRES" (STAR PRESENT) indicator signifies that lock-on (and closed-loop tracking) has begun.

The shutter for the -Y (-Z) STRK can be locked open by selecting ITEM 15 (16). This should be done only after the crewmember has made a visual check out the appropriate window to confirm that no bright object is within 30' of the tracker LOS. The shutter control should be placed in the AUTO mode as soon as possible because direct exposure to a bright source could cause a tracker to fail.

Note: In flight, on rare occasion the crew has had to perform ITEM 15 to manually open the shutter.

3.3.2.1 STRK Target Acquisition

This step occurs during RNDZ operations, as shown in section 4.1.11 and 4.1.21. The steps are shown in figure 3-13; steps dealing with REL NAV are discussed in section 4.1.13.

One of the orbiter IMU's is deselected if the Orbiter is currently operating at the three-IMU level. This is done to force IMU redundancy management (RM) to remain locked onto a single IMU (the lowest numbered one) for

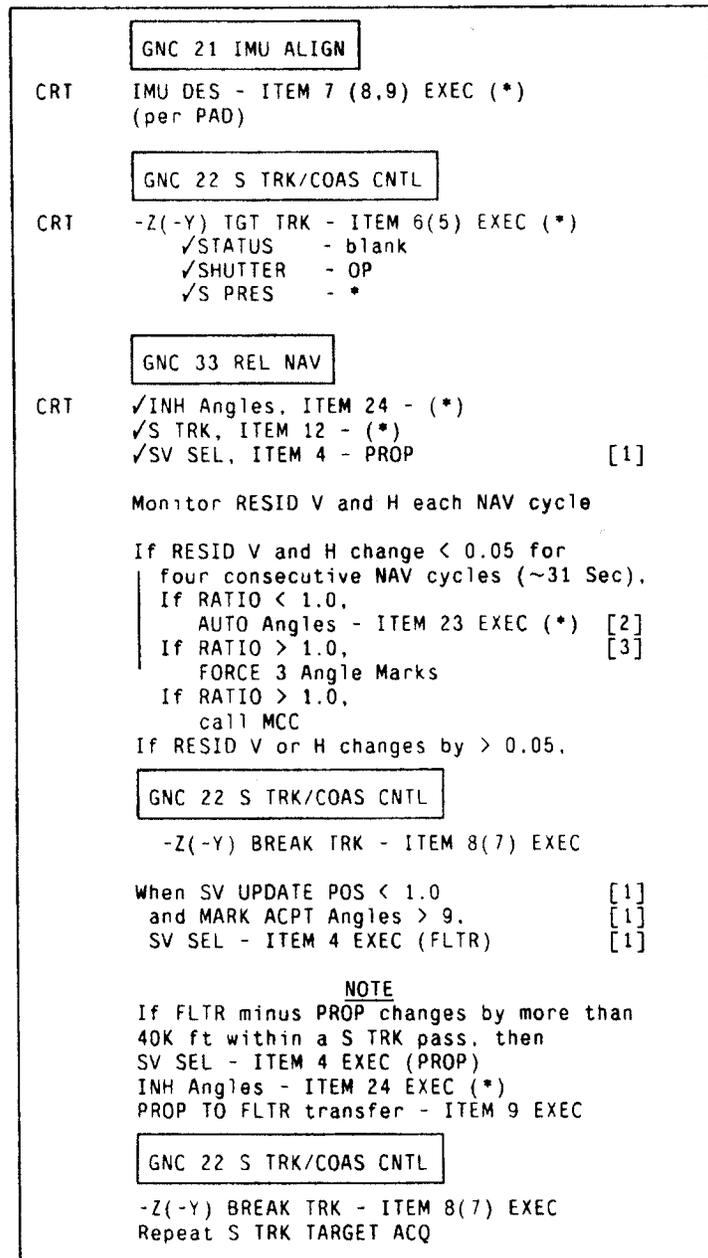


Figure 3-13.- S TRK TARGET ACQ procedure.

Notes:

- [1] Omitted on subsequent acquisitions
- [2] Subsequently, always precede with: FLTR to PROP - ITEM 8 EXEC
- [3] Subsequently, there are three stages for recovery (4.1.22)

attitude data throughout the STRK pass (see section 6.3.4). The reason for this is as follows. At the three line replaceable unit (LRU) level, RM midvalue selects IMU data for use as attitude reference. Under normal operations all three IMU's are closely aligned and RM cycles between the units. Although the slight amount of misalignment between the units is not enough to affect most Orbiter operations, it is enough so that when applied to the STRK data in NAV it adds unnecessary noise to the SV calculations.

Note that the attitude deltas between IMU's is very small and is of concern because the STRK's are extremely accurate pointing instruments, and the slight attitude reference deltas show up as SV updates. When operating using RR or COAS as the source of angular data on the TGT, the IMU deselection is not required due to the granularity of RR and COAS angle data.

Measurement incorporation will be inhibited prior to sensor acquisition. This allows the crew to assess the quality of the data prior to its incorporation into the filter.

The STRK's are commanded to the TGT track mode. This configures the data path such that the STRK software gets its pointing designate information from the NAV function for initial TGT lock-on. The STRK status is also verified satisfactory with no error messages, an open shutter, and an indication of TGT sighting. The informational displays for each tracker (REQD ID through STATUS) work the same way for a TGT as they do for a star.

During its search, the STRK first covers a 1° by 1° cruciform pattern centered about the designated pointing offsets. If a TGT acquisition is not accomplished during the offset scan, the STRK scans the entire 10° by 10° field of view in a raster scan pattern (see fig. 3-14). The offset scan is accomplished in approximately 4 seconds, and the full field scan takes 20 seconds. At the end of this time, if the STRK has still not acquired the target, the STRK waits in idle until it receives another search command. The STRK software issues the search command every 60 seconds.

The "no target" status is displayed after one search has failed, until the next search is commanded.

A bad STRK can be distinguished from a bad NAV state by using the COAS. At STRK acquisition, the crew sights the TGT through the COAS. If the TGT is centered while the residuals and ratios are high, the NAV state is good and the tracker is bad. If the TGT is not centered, the NAV state may be off and the tracker may (or may not) be bad.

To determine if the tracker has locked on to something other than the TGT, the crew must watch the STRK RESID V and H values on the REL NAV display. If the values change by more than 0.05 every NAV cycle, then the tracker has locked on to something other than the TGT. For example, the residuals would change approximately 4° per minute, if the tracker were locked on to an inertially stable object (a star). To force the tracker to resume looking for the TGT, a BREAK TRK should be executed for that STRK. Flight experience has shown that occasional star lock-ons can be expected.

The second STRK acquisition is somewhat modified (see section 4.1.20 and 4.1.22). Procedures for STRK fail cases are discussed in section 4.4.1.

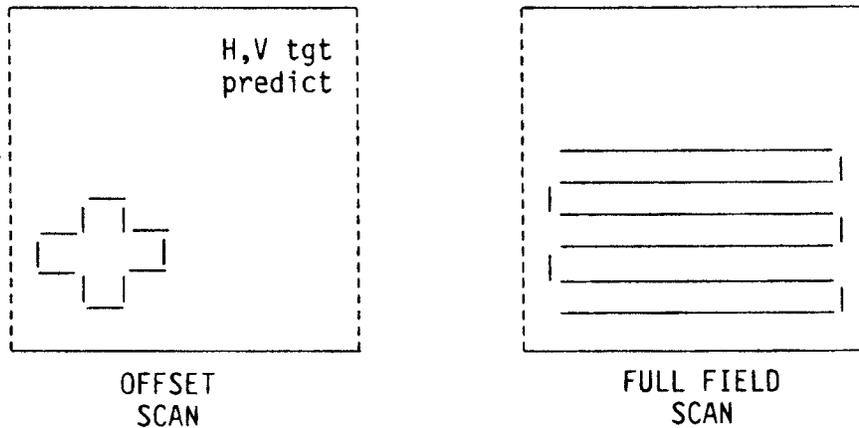


Figure 3-14.- STRK search pattern.

3.3.2.2 End STRK NAV PASS

This procedure is shown in fig. 3-15; it is called out from sections 4.1.16 and 4.1.25 in the RNDZ procedure narrative.

The crew inhibits the sensor data path to the NAV filter in order to be sure that no erroneous data gets incorporated into the SV calculations. The most likely false lock-on would be to a star, and this is quite likely to happen after sunset.

The crew places the STRK's in the terminate/idle (TERM/IDLE) mode to eliminate the cyclic displaying of NO TARGET to the crew while the target is not sufficiently illuminated to support acquisition.

Finally, the crew reconfigures to the nominal on-orbit three-IMU set after the STRK pass is complete.

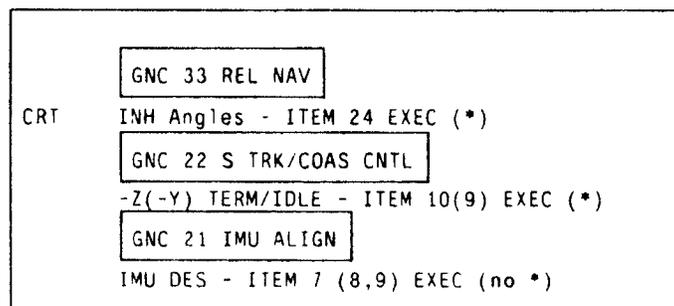


Figure 3-15.- END S TRK NAV procedure.

3.3.3 Crew Optical Alignment Sight (COAS)

The COAS is a sighting unit that can show TGT position relative to either Orbiter -Z or +X axes. The unit bolts into position either on panel 01 in front of window W3 (for +X view, from commander (CDR) seat), or on panel 019 below the aft overhead starboard window W7 (for -Z view, from the aft flight deck). The aft overhead window is the standard COAS position for PROX OPS and RNDZ.

During RNDZ operations, the COAS allows the crew to determine Orbiter body-axis angle measurements of the LOS to the TGT. These angle marks can be input to REL NAV if needed (nominal procedures do not use them). TGT LOS angles observed through the COAS are also crucial to manual control after the final midcourse MNVR (section 4.1.61).

The crew uses the COAS to monitor angular position of the TGT relative to the -Z Orbiter axis. If the Orbiter attitude is maintained fixed relative to the TGT inertial or LVLH frame, the Orbiter position relative to that frame can be determined from these angles (e.g., above or below or off to side of desired LOS). Appropriate translation MNVR's can then be made to correct this position.

Proper determination of desired TGT depression angle during PROX OPS is discussed in section 4.3.6.

3.3.3.1 System Characteristics

There is a 5° radius circle of hatch marks in the middle of the COAS FOV. The entire COAS FOV has a radius of 20° (fig. 3-16). The COAS coordinate system is designated "X, Y" which corresponds to vehicle body coordinates. That is, at the aft crew station, crewmember facing aft, +X is "up" in the COAS (and forward along the Orbiter X axis) and +Y is "left" in the COAS (and to the right along the Orbiter Y axis, facing forward).

The -Z axis is not precisely at 0,0 in the COAS FOV (on 099, for example, it was at -0.562, -0.159 at 15 psi). Cabin pressure levels also have measurable effect on COAS alignment, as the crew compartment ceiling flexes. The crew must perform COAS pointing direction calibration for current pressure level, before NAV use.

3.3.3.2 Position Verification

Observation of the TGT position in the COAS can provide a confidence check on the convergence of onboard NAV (the TGT will get closer and closer to the -Z point, slightly offset from 0,0 in the COAS when the Orbiter is in TGT track mode with -Z axis selected.). Also, troubleshooting problems with the -Z STRK involves looking at the target through the COAS to see if some gross NAV error is mispointing the STRK.

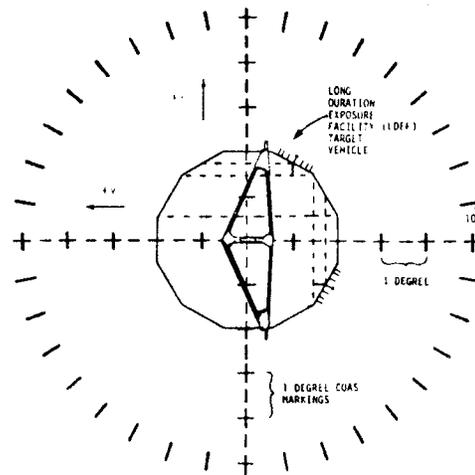


Figure 3-16.- The COAS reticle pattern (-Z view from aft crew station).

3.3.3.3 RNDZ NAV Marks

In a multiple failure case, the COAS can be used to take NAV marks. Since this involves pointing the entire Orbiter (and hitting the ATT REF pb when the TGT reaches the crosshairs), it can be very fuel-expensive and tedious. Generally, one crewmember takes the marks and a second crewmember forces them on REL NAV. The accuracy of this technique remains uncertain.

The operational use of the COAS for NAV is described in section 4.3.3.

3.3.4 Rendezvous Radar (RR)

During RNDZ operations, the RR is GNC's only direct source of R/R-DOT measurements and a secondary source of target LOS angles (STRK angles are more accurate at longer ranges). The RR can also provide angle rate data but when TGT angular size is greater than radar beamwidth (1.6° at 3 dB), beam wandering across the TGT can generate spurious angle rates.

Techniques to enhance radar trackability of the TGT are discussed in section 3.3.10.

The RR shares the steerable 3-foot diameter dish antenna with the Ku-band link to the TDRS. It is a 50-watt pulse system operating around 13.883 GHz, employing frequency agility (cycles through five frequencies to enhance TGT detection and tracking), designed to acquire and track a TGT (with a radar cross section of at least 1 square meter) at a range of 10 miles.

Note: A TGT-mounted transponder could increase that range to 300 miles but no manifested TGT's have such equipment (onboard H/W and S/W could support it). RR hardware design limits skin track ranges to 80 feet minimum and 27.2 n. mi. maximum.

EL and AZ output from the RR are in a body aligned coordinate system centered at the antenna system. The coordinate system is shown in figure 3-17. SHAFT and TRUNNION are in the radar antenna system and RESIDS are computed in that coordinate system.

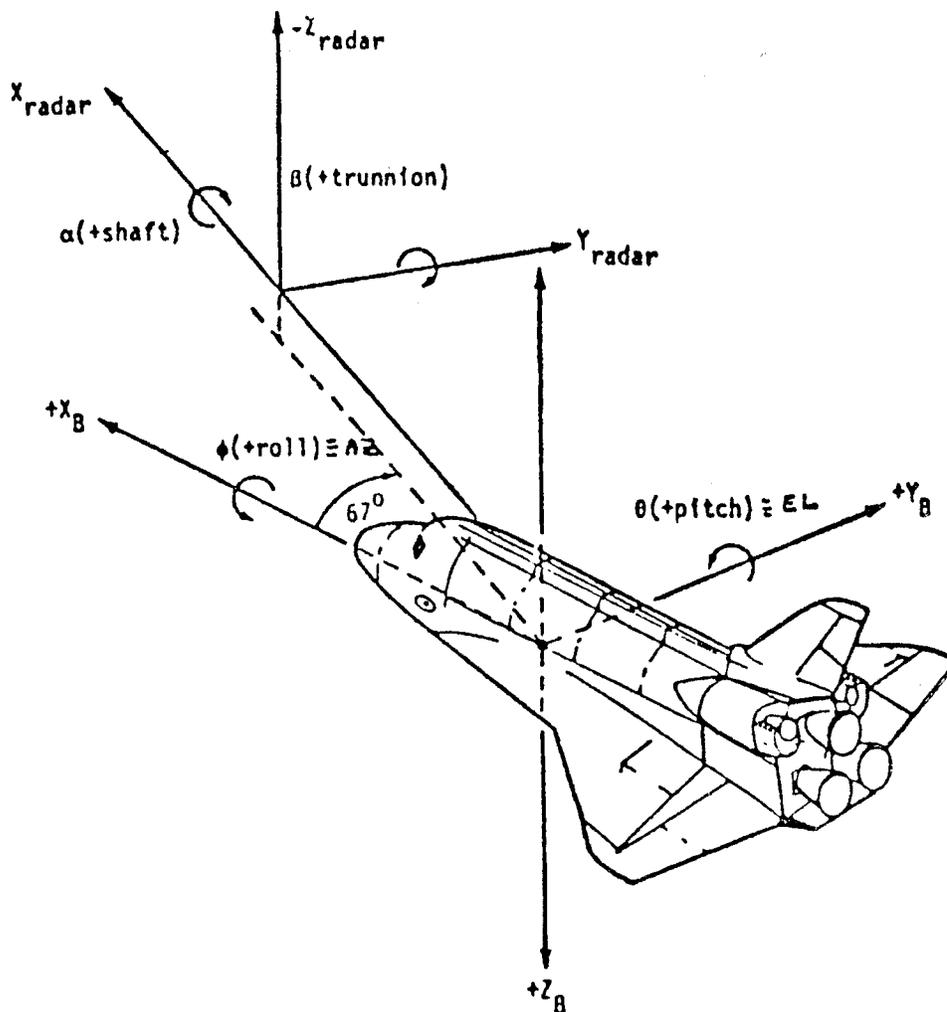


Figure 3-17.- Orbiter body coordinate system and RR coordinate system.

Although the radar can be used in any pointing region not obscured, it is generally assumed that the TGT lies near the -Z axis. In fact, at angles greater than about 30°, radar data becomes too inaccurate for use by RNDZ NAV.

3.3.4.1 Switches

The RR is controlled from panel A1U (fig. 3-18).

The following switch options are available:

- POWER - To go from OFF to STANDBY or ON, warmup takes about 3-1/2 minutes.
- MODE - RDR COOP: Assumes transponder on TGT (see section 8.4.3.2)
 - RDR PASSIVE: Assumes skin track only
 - COMM: No RNDZ function

Note: The antenna pointing depends not on MODE (COMM or RDR) but on whether KU ANT ENA (ITEM 2 on REL NAV) is enabled. When ITEM 2 is enabled, the Ku-band antenna TGT-pointing data is shipped from GNC to the SM GPC. This allows SM to automatically point the Ku antenna at the TGT when the KU ANT switch is in the GPC or GPC DESIG position. This is true whether the MODE switch is in the RADAR or COMM position. When ITEM 2 is enabled, TDRS antenna pointing (ITEMS 12, 13, 14 on SM ANTENNA) via the KU ANT switch is inhibited. The TDRS state vector is still maintained by GNC and will be used when ITEM 2 is disabled. See section 3.4.1.3 for details on ITEM 2.

- RADAR OUTPUT - HIGH, MED, LOW: During SEARCH the RR will be cycled through all power levels at or below the switch setting, lower power first. Once lock-on occurs the power is set to the switch setting. If the RR breaks lock and the system is in GPC, 20 seconds later the search begins again automatically, but power level does not cycle unless the designated range is less than 2550 feet; if the switch is in AUTO TRACK, a new SEARCH must be manually initiated, and power level will cycle. When tracking a TGT at a range of 640 feet or less the power level automatically drops from the switch setting level to bypass mode. Automatic downmoding is required only to protect the receiver, and will not necessarily protect the TGT if track is broken or if a SEARCH is initiated. To protect the TGT, the manual downmoding must be used.

Therefore, in practice, during an approach it is advised to manually switch from high to medium power and from medium to low power at appropriate ranges (2 n. mi. and 1 n. mi. have been proposed for a 1-square meter radar cross section RCS TGT, but in practice a signal strength check will be included). This will keep field strength below 20 V/m on the TGT. This is payload dependent, and usually they want low power inside 800 feet.

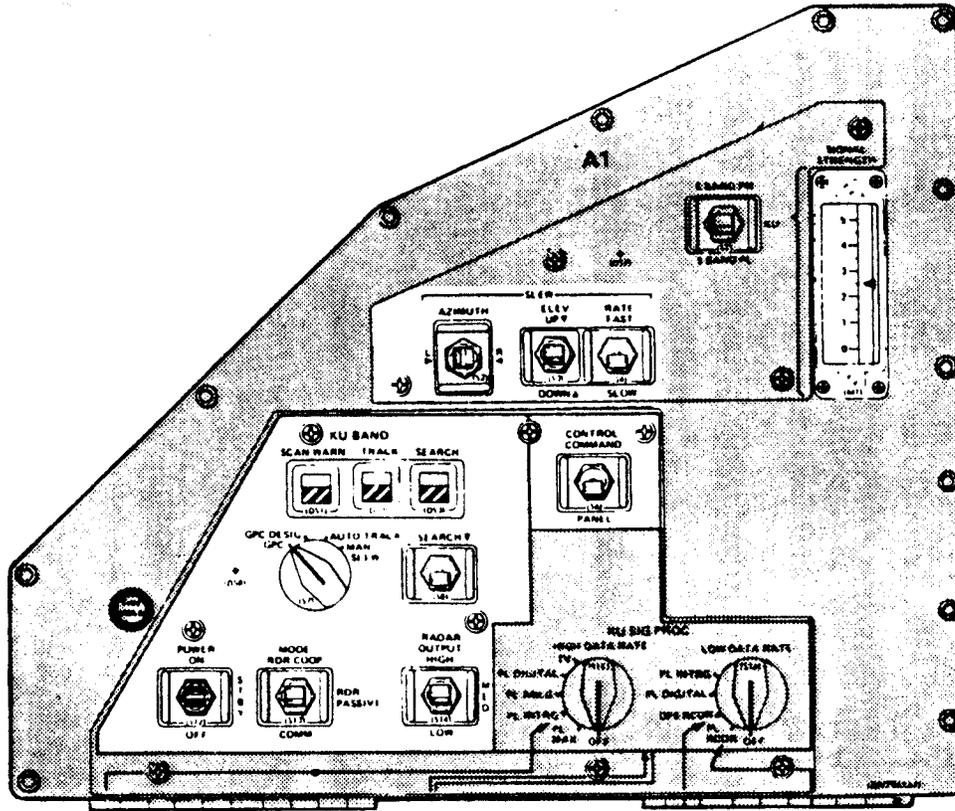


Figure 3-18.- Panel A1U.

- Antenna steering rotary switch (fig. 3-18). These modes and their application to RNDZ are summarized in figure 3-19.
 - GPC: This is "GPC acquisition." The antenna will point to the SM GPC-commanded AZ and EL, and will perform range and closed-loop angle TRK once the TGT is acquired. If the TGT is not acquired, the antenna is automatically commanded to search (in a spiral scan) around the designated point. The angle of search depends on expected range: it is $\pm 30^\circ$ at 8 miles, $\pm 20^\circ$ at 12 miles, $\pm 5^\circ$ at 300 miles.
 - GPC DESIG: The GNC GPC provides a TGT position vector which the SM GPC uses to aim the radar. There is no search pattern initiated. Range/rate data are provided if the SV estimate was close enough and a strong enough signal is returned. No closed-loop angle TRK is provided in this mode, but the designated angles are updated every 2 seconds.

Note: The Ku-band GPC DESIG position should not be selected when the antenna is in the obscuration zone. When the antenna tracks a TGT into the obscuration zone, the GPC reorients the antenna so it can pick up the TGT as it clears the other side of the zone. When GPC DESIG is selected with the TGT in the obscuration zone, the GPC doesn't have any history from which to make a reemergence prediction, so the antenna may rotate around endlessly. This is why the procedures call for RR-AUTO TRK when this situation occurs.

- AUTO TRACK: This begins with manual antenna pointing control, followed by a manually initiated search. The antenna does a spiral scan about the pointing direction at the time search is initiated, at all ranges, to a width of $\pm 30^\circ$. Once the TGT is detected, automatic angle and range TRK is provided. Note: The antenna can be manually slewed in this mode.
- MAN SLEW: The RR is pointed manually; there is no scan, but all ranges are searched within the 1.6° full-angle (for 3dB) cone of the radar beam. If a TGT is acquired, standard range/rate data are provided. To break track on a TGT, go to MAN SLEW, then slew the antenna away a few degrees until the TRACK talkback (tb) goes barber pole (bp).

Note: Valid RR angle data is available only in GPC or AUTO TRK modes and if the antenna is free to slew.

- SEARCH (momentary contact) - This command only works if the rotary switch is in AUTO TRACK and no TGT is currently being tracked. The antenna will then begin a spiral search pattern.
- CONTROL - PANEL: The panel switches have absolute control.
 - COMMAND: The only functions which can be commanded from the ground via the ground control interface logic (GCIL) unit despite the current position of the power and mode switches are: COMM power ON/STANDBY/OFF.

Note: Regardless of the control switch position, the ground can uplink six command loads to the SM GPC which will configure the Ku-band system via the serial input/output (SIO): KU/serial I/O enable, range estimate AUTO/MIN, radar self test ON/OFF, antenna inertial stabilization ON/OFF (GPC designate mode only), obscuration mask ON/OFF, and traveling wave tube (TWT) amplifier ON/OFF. There are no current plans to utilize this capability.

- SLEW - These switches allow manual slewing of the antenna. Two rates are allowed: low (0.4 deg/s) and high (20 deg/s). Elevation and azimuth are defined in an Orbiter body frame (see figure 2-16) along the -Z axis, with elevation corresponding to Orbiter pitch (+ is toward the nose) and azimuth corresponding to Orbiter body roll (+ is toward the right looking out OH window; i.e., the port wing).

	Uses TGT SV for ant EL, AZ	If not pointed at target*	Angles good to NAV and ADI LOS needles	Perform closed-loop tracking	Rendezvous/ PROX OPS phase usage
GPC ACQ	Yes	Search angle dependent on expected range	Yes	Yes	Normally, always on approach
GPC DES	Yes	No search	No	No	Never (TDRS COMM only)
AUTO TRACK	No	Search to $\pm 30^\circ$ angle	Yes	Yes	Backup mode to GPC ACQ. Likely to be needed post deploy, then switch to GPC ACQ after NAV converged
MAN SLEW	No	No search	No	No	Possibly for space station at $R \leq 2-3n.mi.$

* If pointed at target, RR locks on in all modes.

Figure 3-19.- RR steering modes.

- SIGNAL STRENGTH meter - This shows how much power is being reflected back from the target and is a function of range, transmitted power, and radar cross section.
- TALKBACKS - TRACK is gray if tracking, bp otherwise.
 - SCAN WARN is gray if the beam is within about 5° of the Orbiter body, bp otherwise. When SCAN WARN is on, RF transmission is disabled, but this has been overridden. So for RR OPS the indicator is a NO OP.
 - SEARCH is gray if searching, bp otherwise. After 1 minute maximum, SEARCH automatically times out. It will repeat in GPC acquisition mode about new designate angles after a 20-second delay.

3.3.4.2 Parameters

Range, range rate, azimuth, and elevation are measured along the LOS to the TGT (The RR directly measures relative range rate via Doppler tracking of the TGT). The values are displayed on the REL NAV SPEC function (section 3.4.1) and on an aft crew station dedicated display meter (select R/R-DOT or EL/AZ).

The RR data are displayed on panel A2 (fig. 3-20) with a pair of LED digital displays which represent either range (in kft) and range rate (in ft/s) or (depending on position of the DIGI-DIS SELECT switch) elevation and azimuth angles (degrees, Orbiter -Z reference). The elevation and azimuth inertial LOS TGT angle rates (in mr/sec) are always displayed on a two-D meter (scale is selectable, X1 or X10); the mr (milliradians) unit is useful because multiplying mr/s by range (in kft) gives normal to line of sight (NLOS) rate in ft/s, with respect to an inertial frame centered on TGT. The elevation and azimuth angles and rates allow maintenance of Orbiter position on the TGT V-BAR, even in darkness when the COAS is not usable (see section 4.3.6 for desired c.g.-offset depression angles).

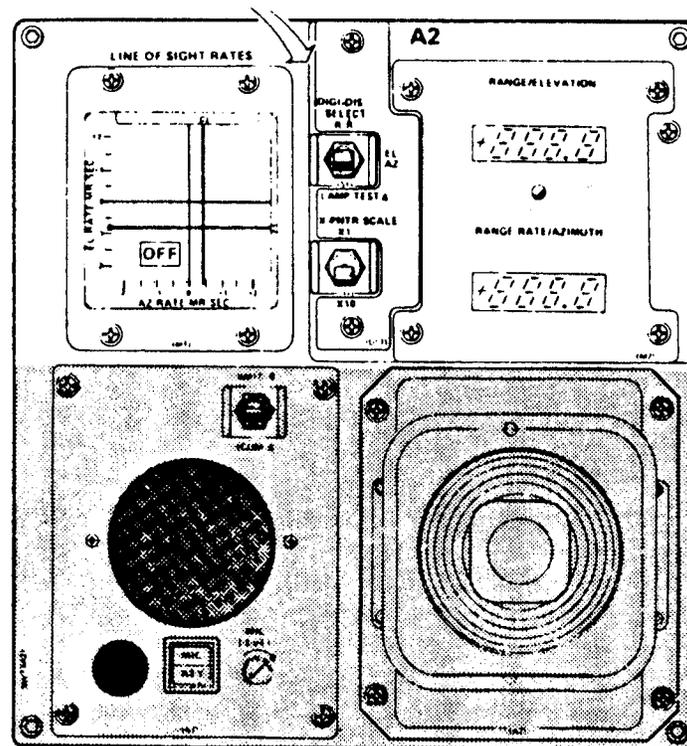


Figure 3-20.- Panel A2.

The elevation and azimuth inertial LOS angle rates provide information on relative position rates normal to the LOS to the TGT and are independent of Orbiter body attitude as they are referenced to the radar gyro (inertial reference) frame. Once close to the TGT, they become unusable due to beam wandering and random relative motion. In fact, flight experience indicates that, at all ranges, LOS rates as displayed on panel A2 jitter far too much to be useful as procedures criteria. Proper filtering may improve this.

A "detect" flag is set (but not displayed onboard) when a return signal is first received. Once the return passes a Ku-band electronic assembly internal validity check, "DATA GOOD" flags are set and closed-loop tracking can begin. The data can now be used in REL NAV.

3.3.4.3 Other ANTENNA display (SM 201) options

The use of AUTO/MIN options for RDR RNG is as follows (ITEM 1/2):

- AUTO - SM GPC outputs AZ and EL angles and estimated range to the TGT which was computed by the antenna management software from TGT position vector provided by the GNC GPC.
- MIN - Forces the SM GPC to output AZ=0° and EL=0° (-Z axis line of sight) and an estimated range of 2400 ft. This setting is typically used for acquisition after separation, at close range.

The use of RDR THOLD (ITEMS 3 and 4) to select heavy or normal low clutter environments is not part of any conceivable rendezvous or PROX OPS procedure. The option was implemented to handle a problem that was later fixed in hardware, and the feature will be deleted at the next convenient software scrub.

3.3.4.4 Self-Test

The Ku-band system is put through a self-test of its circuitry early in the RNDZ phase. While the self-test in itself is not always an absolute indication of a failed or operational radar system, it does provide insight into the system should some anomaly become apparent later in the profile.

The system is configured to the RDR PASSIVE mode for self-test. The system can be tested in the COMM mode, but in the RDR PASSIVE mode the radar processor is tested as well as the electronics assembly and deploy mechanism. For self-test to pass, the radar system power output must be at HIGH.

The system control is put to MAN SLEW to keep the antenna from receiving gimbal commands to follow the TDRS at the completion of the test. One of the system peculiarities occurs when the system is placed into the communications mode while the TDRS is obscured by Orbiter body blockage. In this situation, the antenna could possibly begin oscillating from one gimbal stop to another until the TDRS exits blockage.

When the panel is properly configured, the system control is transferred from ground command to onboard by selecting CNTL - PNL.

The SIGNAL STRENGTH meter is set to register for Ku so the crew can monitor the progress of the self-test; range/range rate is selected on the digital display so the crew can tell if the system passed or failed self-test; and cross pointer scaling is set to its high resolution display so the crew can more accurately monitor LOS rates during PROX OPS. Self-test is initiated via the appropriate item entry on the SM ANTENNA display and lasts about 3 minutes. During the test, several simulated TGT inputs are sent through the system, and the crew will see the SCAN WARN, TRACK, and SEARCH panel talkbacks cycle to gray from barberpole. At test completion, a pass (888.8) or fail (333.3) indication will be given on the digital display (panel A2) and on the REL NAV display in the range slot.

At test conclusion, the crew cancels the self-test command (ITEM 7) and reconfigures the Ku system. Before going back to ground command, the mode switch is put back into COMM, but the antenna pointing is not reconfigured back to GPC from MAN SLEW to avoid gimbal oscillations. During the next ground acquisition of signal (AOS), the MCC will verify that the TDRS is not in blockage before configuring back to GPC pointing control of the antenna.

Flight experience has shown that the RR self-test has failed about half the time, but the RR has always performed properly for RNDZ and PROX OPS.

3.3.4.5 Configure for RNDZ Radar TGT Acquisition

This procedure is shown in figure 3-21A; it is called out in section 4.1.18 of the RNDZ procedures rationale narrative.

GNC 33 REL NAV	
CRT	KU ANT ENA - ITEM 2 EXEC (*) GNC. I/O RESET EXEC
A1U	KU MODE - RDR PASSIVE KU - GPC ✓KU RDR OUTPUT - HI KU CNTL - PNL
A2	DIGI-DIS SEL - R/RDOT

Figure 3-21A.- configure for RR
TARGET ACQ.

Because of the pulse repetition techniques used by for the RR, the maximum possible unambiguous range for TGT acquisition is just under 164 kft (27 n. mi.). To avoid acquiring confusing and inaccurate data at longer ranges, the system is configured to the radar mode after the Orbiter-to-TGT predicted range is less than 150 kft.

Speed of electromagnetic waves multiplied by pulse repetition frequency of the RR system while in long range track mode gives the total distance traveled by one RR pulse before the next pulse is sent. Dividing by 2 gives the one-way distance from Orbiter to TGT that allows a single RR pulse to be sent, reflected off the TGT, and returned to the Orbiter before another RR pulse is sent.

If the RR did acquire a TGT at longer ranges, a second RR pulse would have already been sent by the time the initial pulse was returned. In this case the RR would interpret the returning initial pulse as being a return of the second pulse off of a TGT close to the Orbiter. The interpreted TGT range would be approximately 164 kft less than the actual range to the TGT.

The radar is put into the RDR PASSIVE mode for TGT's without radar transponders on them (the RDR COOP mode for aided TGT's has not yet been validated on the STS). The KU switch is placed in the GPC position so that

the radar can automatically receive pointing estimates for where to search for the TGT from the Orbiter GPC's. In the GPC mode of operation, the RR performs a spiral search for the TGT every 80 seconds until lock-on. The search pattern begins at the GPC designated gimbal angles and covers a 30° half angle cone. The spiral search takes 60 seconds to complete, after which the RR receives new designate angles, drives to those designates, and waits for the next search command. HIGH power on the RADAR OUTPUT switch is required to support TGT acquisition at maximum ranges. Once the panel has been properly set up, the control of the radar system is transferred from ground command (CMD) to onboard control panel (PNL) via the KU CNTL switch.

Interface software is set up for the Ku system to receive pointing designates from the GN&C software for the RNDZ TGT by executing KU ANT ENA. Without this item executed, the Ku designates come from the SM software and are for the TDRS satellite selected for communication. The GNC I/O RESET executed later initiates this interface processing.

NAV software is configured such that angle data will be input from the RR system instead of the STRK or COAS by executing ITEM 13 on the REL NAV display. Even if angles are still selected from STRK or COAS, the R and R-DOT are exclusively from the RR and are thus always selected (there is no choice).

The DIGI-DIS SEL is set to monitor range and range rate. Until lock-on, this value will be zero and will show data only after the TGT is detected. If the meter were configured to display AZ and EL, the crew would see the designated pointing angles displayed prior to acquisition and then actual angles after acquisition. Since designate angles should be close to actual, if the panel were set to angle data, it would not be obvious by viewing the meter if an acquisition had occurred or not.

Whenever either RR angle exceeds 30°, radar angle measurements will be inhibited by crew action. This is because angle data is considered valid only within a band plus or minus 30° from the line-of-sight of the RR. (Ref: Onboard Navigation Systems Characteristics, Dec. 1981, section 7; JSC-14675; 79-FM-5, Rev 1)

3.3.4.6 RR Cue Card

A standard procedure for RR AUTO TRACK acquisition is shown on the RNDZ OPS cue card below (fig. 3-21B). The antenna is manually pointed towards where the TGT really should be; if lock-on still fails, return to GPC/ACQ mode (pointed by NAV), and the last hope is that target radar reflectivity characteristics (range and/or attitude) will improve enough to allow acquisition.

```

KU - AUTO TRK
Slew antenna to Elev 0, Az 0
(or Elev, Az as seen in COAS)
√Ku TRACK tb - gray
If no TRK,
  KU SEARCH - SEARCH (tb-gray)
If no lock-on within one minute,
  KU - GPC

```

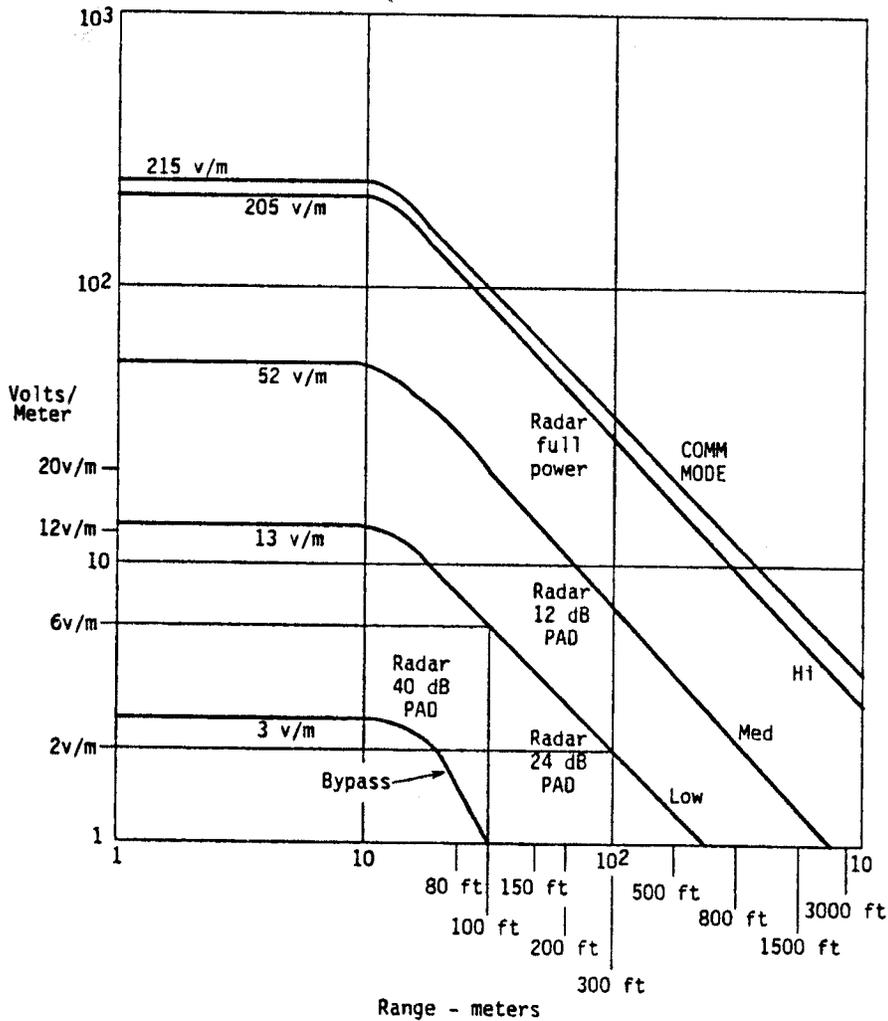
Figure 3-21B.- RR AUTO TRACK ACQ.

3.3.4.7 Radar Effects on Target

The electromagnetic pulse from the Ku-band antenna must be powerful enough to allow a sufficiently strong echo to return off the TGT. Since inverse square law dissipation occurs on both the outbound and inbound legs, the total energy loss follows an inverse fourth power law. This feature suggests that a radar powerful enough for tracking an object several miles away could be powerful enough to damage its electronics when it gets to within several hundred feet. This is true, even with the option of reducing power during approach (see section 4.1.62 for a discussion of these procedures).

Figure 3-22 shows the induced electrical charge in volts/meter caused by the Ku-band radar at its four power settings, as a function of range.

When operating in any power mode, when the Ku-band system detects range < 640 feet it will automatically command "bypass power," which reduces power to 40 dB below high (there is no other way, either from onboard or MCC, to instigate this mode). If the system breaks lock it will jump to the power setting on the panel (HIGH, or MEDIUM [12 dB below HIGH], or LOW [24 dB below HIGH]) momentarily before detecting R < 640 and resuming "bypass mode".



10589*005

Figure 3-22.- Induced volts/meter on target.

3.3.5 Closed Circuit Television

Although installed for other purposes, the CCTV's are also used as important range/rate sensors.

The fields of view of the CCTV's are as follows:

There are normal lenses (usually on the PLB A, B, C, and D cameras and the RMS EE) with focal lengths of 18 mm to 108 mm (zoom of 6:1) and wide angle lenses (RMS elbow and sometimes per PL request on PLB B and C) with focal lengths of 8.2 mm to 25 mm (zoom of 3:1). The following values apply for focus set to far and underscan on, and they refer to the horizontal scale on the CCTV monitor, in degrees: normal-lenses zoom-out is 40.9, zoom-in 6.6; wide-angle lenses zoom-out is 83.3, zoom-in is 29.5.

Note: Adjusting the focus will affect the width of the normal lens FOV, with zoom-out FOV changing from 40.9 to 33 as the focus is changed from "far" to "near," and zoom-in FOV changing from 6.6 to 5.8 as the focus is changed from "far" to "near"; however, for rendezvous and PROX OPS, the focus will always be set to "far." With the wide lens, changing focus will hardly affect width of FOV at all.

3.3.5.1 Locations

There can be four bulkhead-mounted CCTV's in the PLB, designated A (forward port), B (aft port), C (aft starboard), and D (forward starboard); two RMS cameras (elbow and wrist); and possibly keel and pallet cameras. Selection and control of camera operations is made via panel A7U (fig. 3-23); the two monitors are on panel A3 (fig. 3-24). Camera pan and tilt angles are shown on the CCTV monitors in the monitor "data on" mode.

3.3.5.2 Control/Display

On each of the two CCTV monitors, the camera ID, pan, tilt, and camera over-temperature can be displayed (selectable via the DATA SWITCH ON/OFF on the monitor). Crosshairs can also be displayed (selectable via the X HAIR ON/OFF toggle switch). Two camera scenes can be multiplexed onto one monitor, but in this case only camera ID information can be displayed; neither pan/tilt nor crosshairs can be displayed.

3.3.5.3 Triangulation Technique

Forward and aft bulkhead camera tilt angles are obtained by the crewmember after the TGT has been centered in the FOV (fig. 3-25). By use of triangulation (see chart, fig. 3-26), the range to the TGT can be determined (it is then biased by the distance from the forward camera to the roof of the crew compartment, to provide a pure "clearance" reading where "0" is contact). The error sensitivity of this technique is a function of tilt angle, and the range estimates become degraded at angles of greater than about 80° (ranges greater than 200 feet).

The CCTV cameras must be "zeroed" ahead of time and possibly during RNDZ phase if the tilt encoders are disturbed. This is done in the CCTV CONFIG block by pointing camera A at camera B (and vice versa) and hitting PAN/TILT-RESET switch for both; repeat for cameras C and D.

See section 4.3.6 for values of forward (FWD) PLB CCTV tilt angle on V-BAR, as function of range.

3.3.5.4 Keel/Pallet

For some payloads (e.g., LDEF or TSS), one or more of the bulkhead cameras may be remounted inside the PLB. A keel-mounted camera will look right up

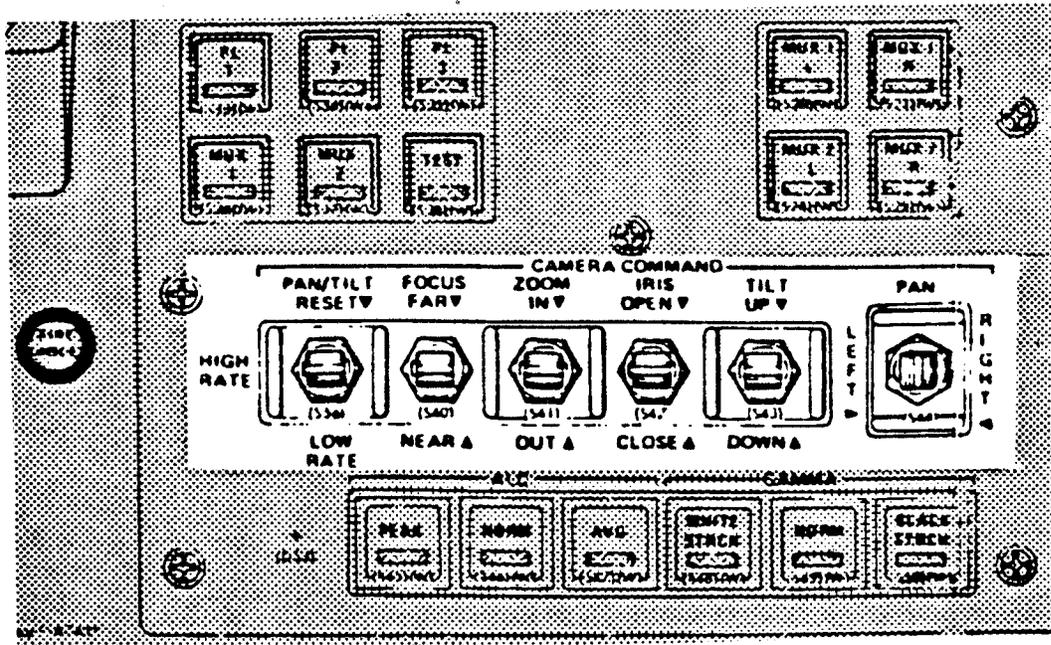


Figure 3-23.- Panel A7U. Camera command & video input/output.

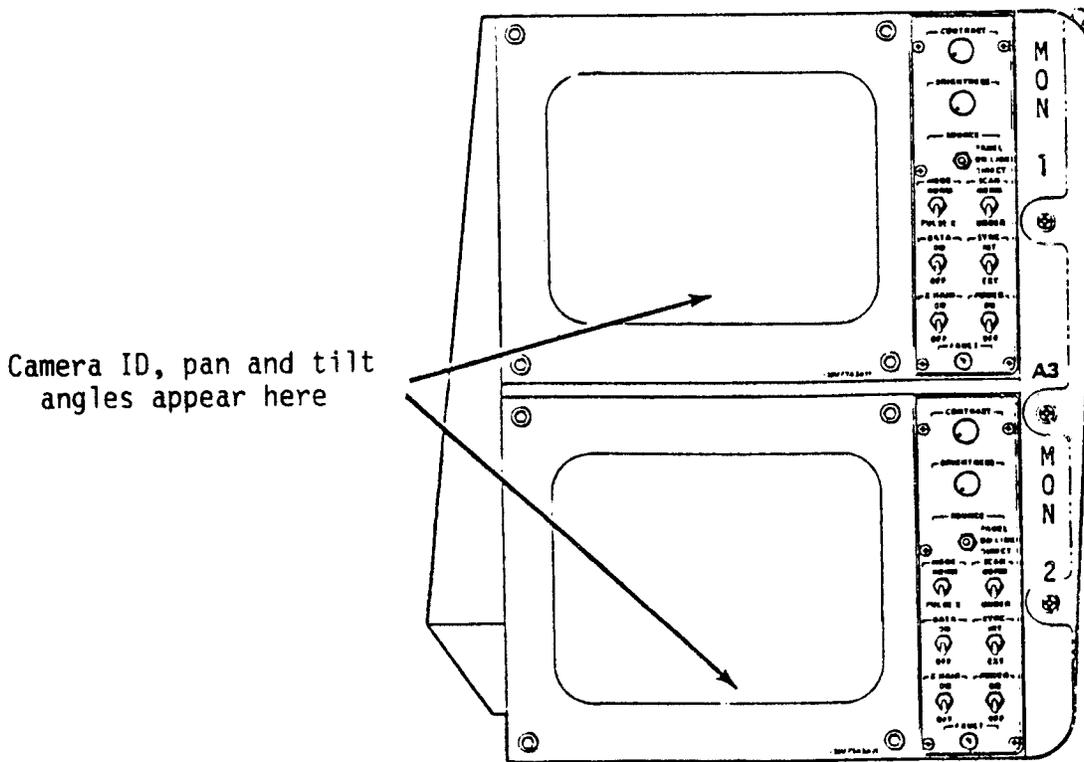


Figure 3-24.- Panel A3.

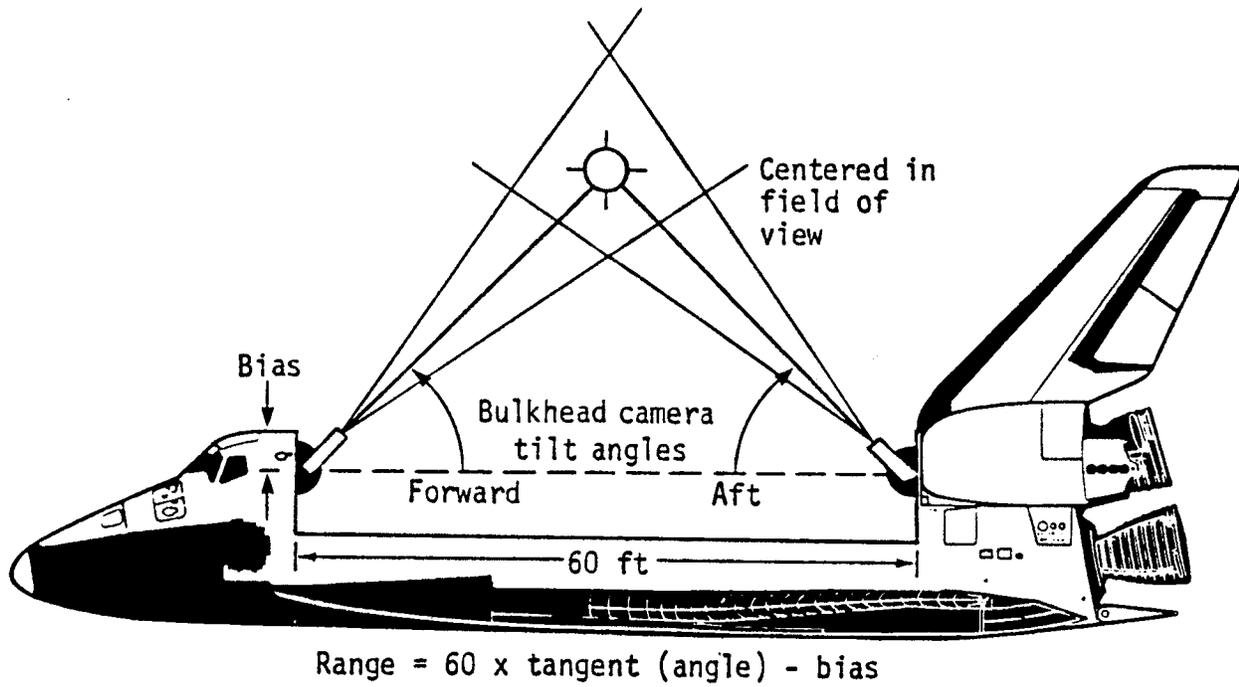


Figure 3-25.- Use of bulkhead cameras tilt angles to determine range.

CAMERA ANGLES AND RADAR ANGLES RANGING CHART

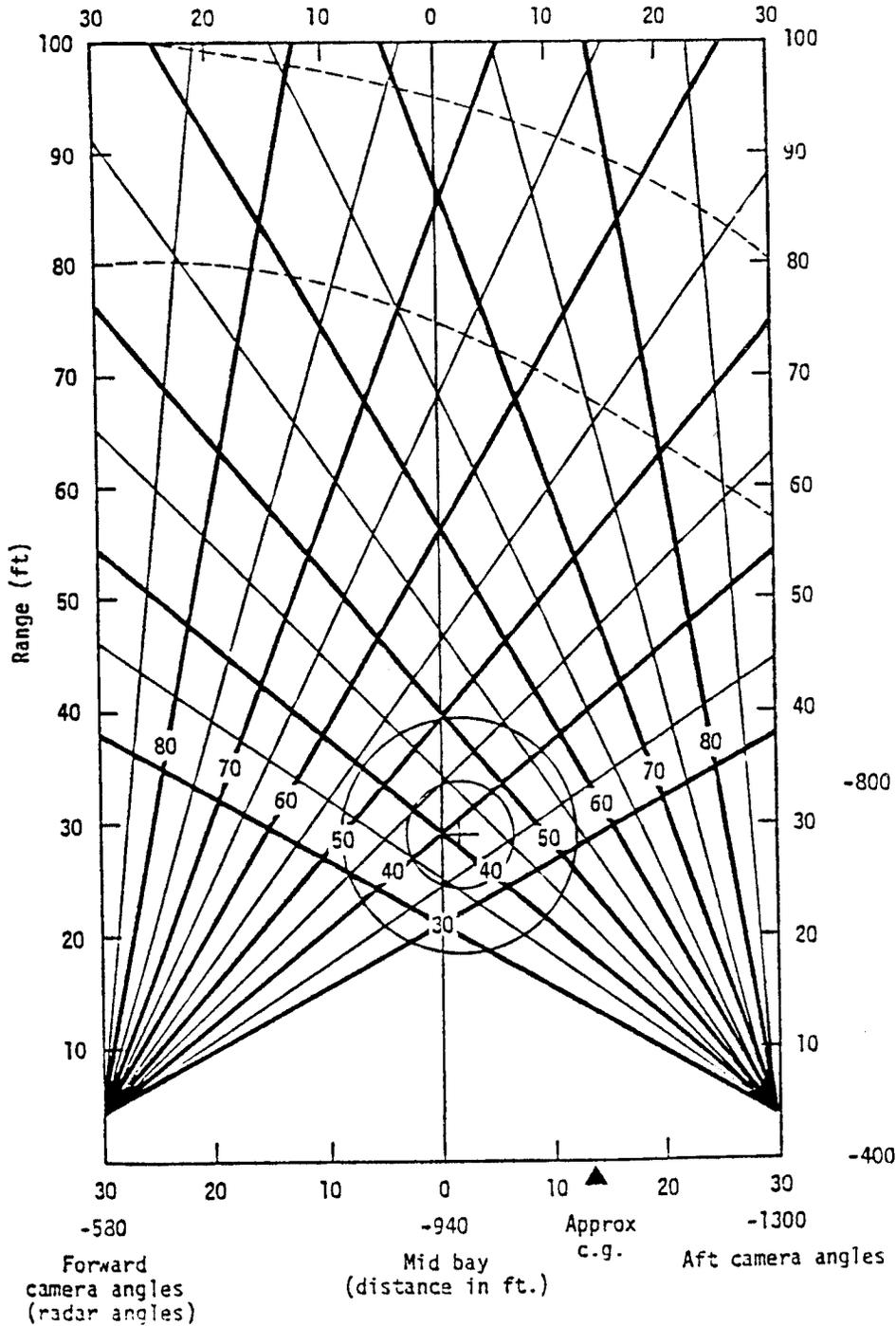


Figure 3-26.- Triangulation chart.

(Note: RMS EE coordinates also provided here.)

the -Z axis; it will have no tilt/pan control. Both Orbiter X and Y axis deviations can readily be detected and controlled using such a view. (See fig. 3-27.)

3.3.5.5 RMS Wrist

With the RMS in grapple position, the wrist camera FOV is normal to the -Z axis. Motion of the payload in this view is the prime indicator of fine closing rates just prior to final stationkeeping and grapple (fig. 3-28a). Rates along Orbiter X axis are also monitored here.

The RMS elbow camera (if installed) could be used as a backup to the RMS wrist camera. Pan/tilt orientation for this camera must be manually adjusted. In such a case, it might be preferable to perform grapple over the COAS, using aft bay CCTV's for rate measurement. See section 4.4.6 for failure recovery discussion.

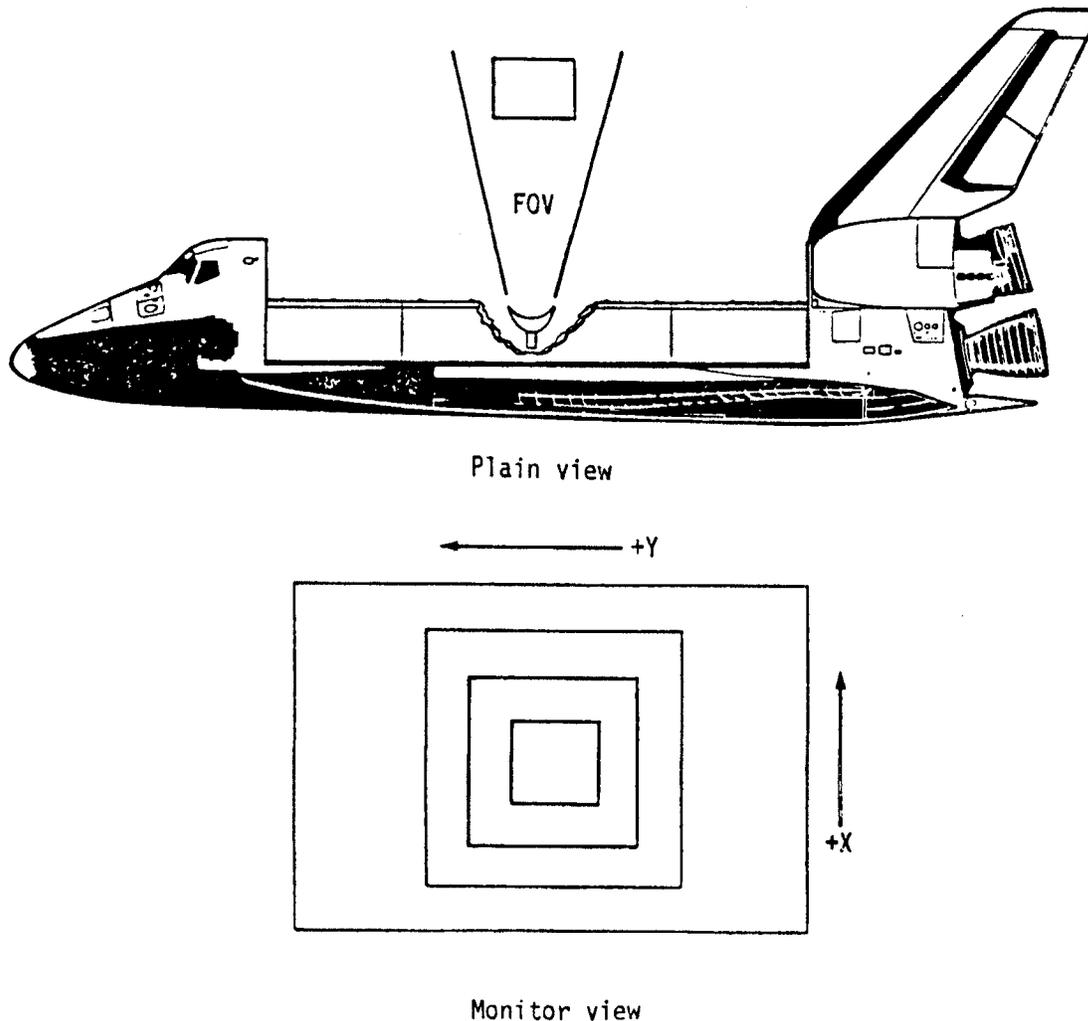


Figure 3-27.- Keel camera.

As an aid to visualizing Orbiter-relative motion of an object being observed in the EE CCTV, a transparent overlay (fig. 3-28B) is included in Flight Data File (FDF) for installation over the appropriate CCTV monitor.

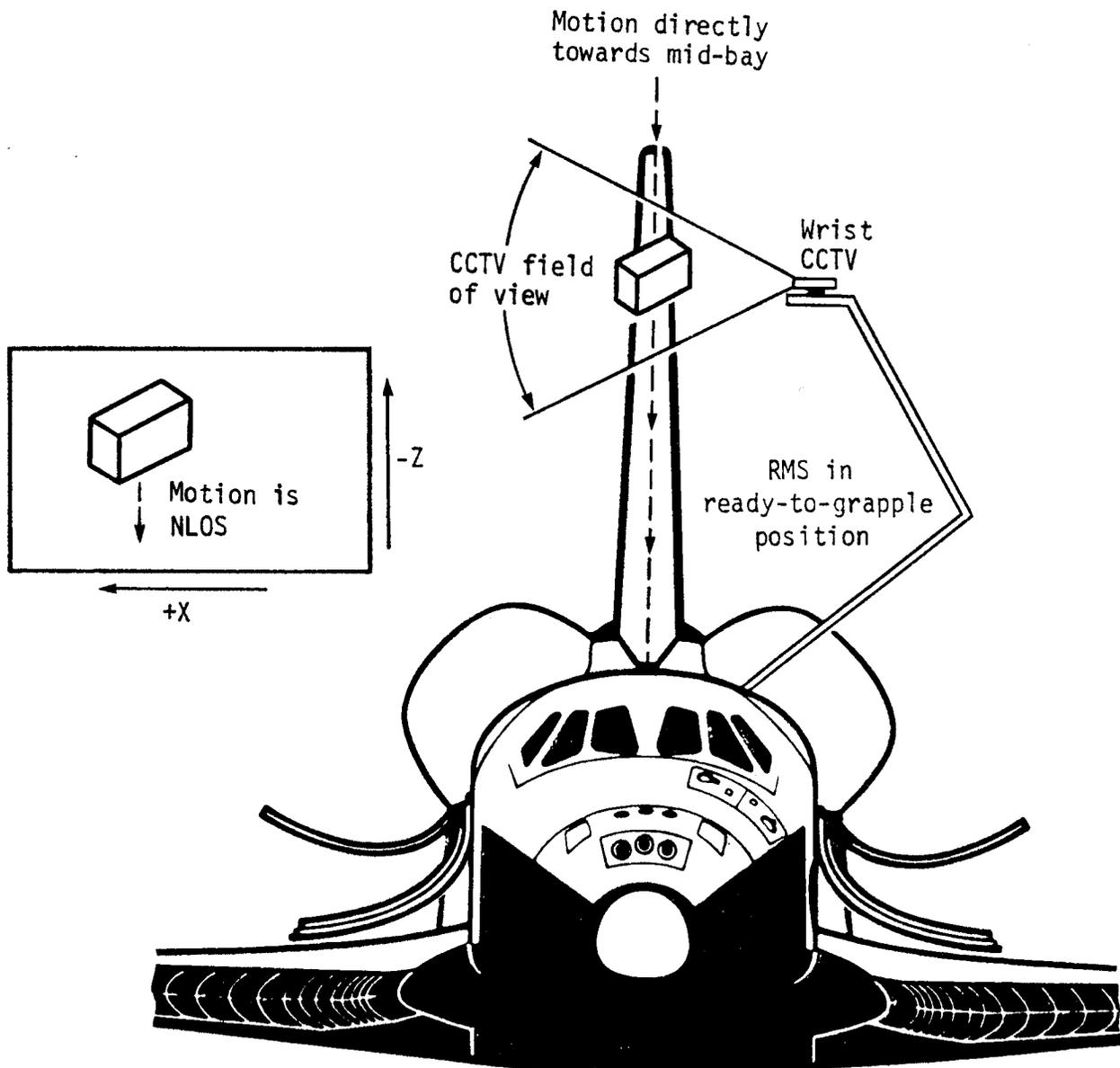


Figure 3-28A.- Use of RMS wrist camera to determine range rate.

3.3.5.6 Other PLB cameras

Depending on mission cargo mix, there may be other CCTV's in the PLB viewing up the $-Z$ axis (e.g., Earth observation systems). Their utility to RNDZ and PROX OPS must be determined on a mission-by-mission basis.

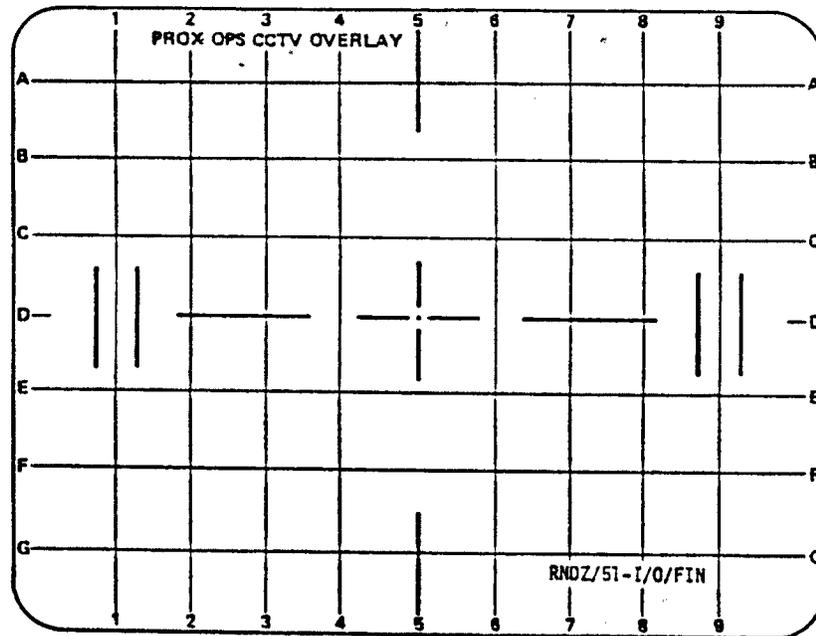


Figure 3-28B.- EE CCTV object motion overlay.

3.3.6 CCTV/Overlay

A variety of methods exist to estimate distance to a TGT in the event of radar failure. Within 200 feet, CCTV elevation angle is used, and COAS subtended angle can be used out to about 1000 feet, depending on the size of the TGT. A crewmember's binocular vision can provide excellent ranging estimates out to 60 to 80 feet; judgements based on TGT angular size are probably good to 200 to 400 feet, depending on TGT size. A combination of hardware, geometry, and human factors limitations degrade the accuracy of these methods as range increases. The most reliable technique is use of TGT angular size on CCTV screens.

In current practice, if the radar is failed, there is only one method of determining range at distances much beyond 1000 feet with reasonable accuracy. For payloads the size of Solar Maximum Mission (SMM) or long-duration exposure facility (LDEF), range can be estimated from about 40 to 6000 feet, with a mean error (based on SES experience) of about 3 percent to 4 percent. Procedurally, the crew configures the CCTV cameras for either full or no zoom. The TGT is approximately centered, then the bottom line of the applicable range ruler (fig. 3-29) is placed atop the screen image of one end of the optimum axis. Range is read where the other end of the axis falls. A gross estimate of range rate may also be obtained using the rulers and a stopwatch or HP41CV program, although SES experience shows that range rate accuracy is poor (mean error of 50 percent). Essentially, the rulers can only be relied upon to provide a "sense" of the range rate; e.g., opening or closing; fast or slow. In practice, it is best to wait until two or three ruler hacks are taken that give consistent R-DOT, before performing translation to adjust R-DOT. However, it may not be possible to wait that long.

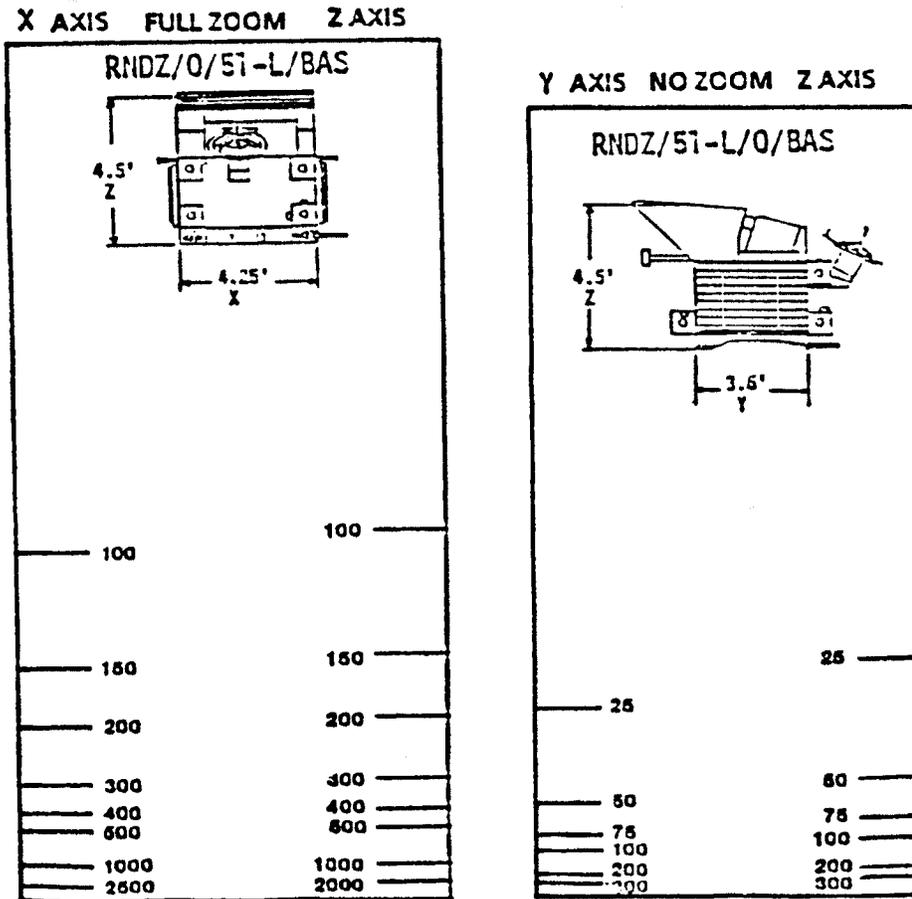


Figure 3-29.- Typical ranging overlay.

Flight experience has shown that image blooming caused by overbrightness from Sun reflections off the TGT can seriously degrade the utility of this procedure. The displayed CCTV image can be rendered useless during these phases. Current CCTV H/W improvements may help with this problem; manual camera iris control is also useful.

Note: Underscan should be selected on the CCTV's when using the ranging rulers. The rulers can be made either way, but are made up for underscan because DOD requirements for downlist TV preclude the use of operating without underscan. Underscan (switch selectable) creates a blank border around the CCTV monitor image, which insures that no edge overlap scenes are being downlinked. However, it also results in a 6 percent reduction in image size on the CCTV monitor.

3.3.7 Other Ranging Devices

3.3.7.1 Laser Rangefinder

A laser rangefinder was operated on early RNDZ missions. Originally conceived as part of an AUTO-focusing system for the CCTV system, it was mounted on a PLB TV camera, and range and range rate readouts were displayed on a CCTV screen. The device was effective out to a range of perhaps 400 feet. Experience was unsatisfactory and this particular device was not used subsequently.

In principle, such devices (with improvements) can be very useful as close range sensors for space station docking. With ranges of up to several miles, such devices make terminal phase much easier, especially when range and rate data can be fed directly into NAV. Hardware development is underway on such a device.

3.3.7.2 Stadimetric Binoculars

This optional equipment, first flown on STS 51-A and highly recommended by the crew, consists of 8X binoculars with tick-marked reticle (5-milliradian increments). In conjunction with an HP41C program for angle-to-range conversion, it provided an accurate and easy-to-use backup ranging device.

3.3.7.3 Global Positioning System

Use of the global positioning system (GPS) for relative NAV may someday be feasible. Equipment on both Orbiter and TGT process GPS data and then difference the pseudorange data for relative motion NAV. This technique would allow GPS systematic biases to cancel out. For a single user, expected accuracy is to within 35 feet in position, and 1 ft/s in rates; however, relative positions would be accurate to within 3 to 10 feet. Use of this technique would require new NAV software in the Orbiter, and to date this has not been approved.

3.3.7.4 Other

Other NAV technologies have been proposed for determining the SV of the Orbiter. These include "TACAN NAV" and "TDRS NAV." Neither has been implemented or scheduled, and thus they have no relevance to current or planned RNDZ operations. Advanced systems for space station RNDZ NAV are discussed in chapter 8.

3.3.8 Orbiter Lights

For nighttime viewing of TGT's through the COAS along the -Z axis, a spotlight is mounted on the forward PLB bulkhead and projects a 10° beam

(half intensity at edges). The light is a 230-watt metal halide device providing about 1200 candlepower. Brightness is sufficient to determine TGT attitude at 700 feet, where the beam width is about 100 feet. The light is controlled from a switch on panel A1.

The six PLB lights already installed do provide some nighttime TGT illumination capability, but the overhead docking light increases intensity in its beam by about 30 percent. At low light levels this is quite significant.

There is also another light atop the CCTV on the RMS wrist. Note that for PL's in the bay, some or all of the PLB lights may have to be kept off for PL thermal constraints.

A specialized portable xenon light (called the "streamlight") is available as an optional item for night stationkeeping. It throws a lot more light (one million candlepower) than regular Orbiter lights, and crews (the first was 51-A) highly recommend it. The light is fastened on a camera bracket at one overhead window and plugs into utility power; stowed, it and its own power converter take up one full middeck locker. It is a big power user and gives off a lot of heat. In-cabin use is constrained by window transmissivity.

3.3.9 Target-Mounted Sensors

Some TGT's have their own attitude sensors and make such data readily available for display onboard the Orbiter and on the ground. Where such attitude data exists or can be derived, every effort should be made to make it available to the crew during PROX OPS.

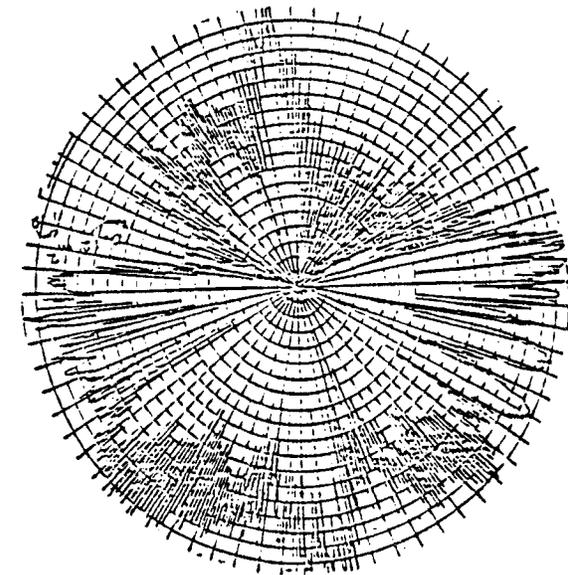
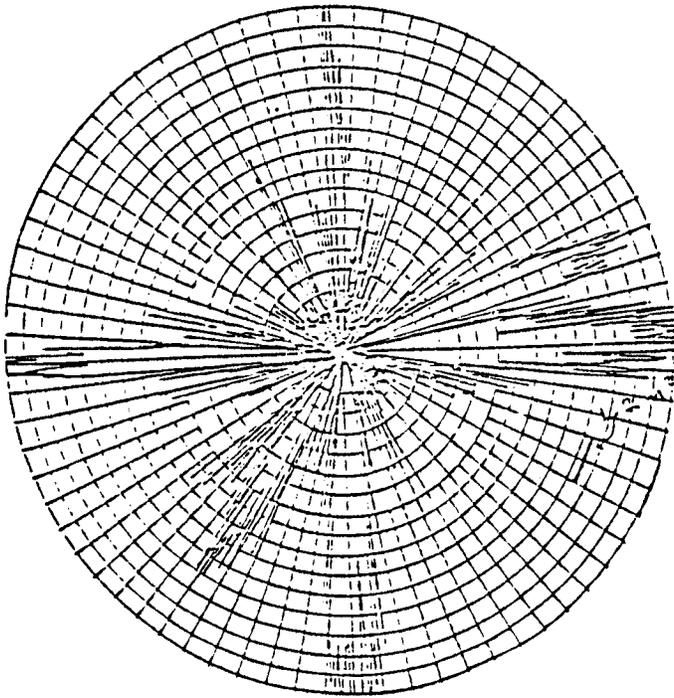
3.3.10 Target-Mounted Tracking Aids

Various TGT characteristics are desirable for enhancing the ability of the Orbiter crewmember to determine TGT range and attitude.

In terms of visual tracking, it is desirable that the TGT not have high-gloss surfaces which can cause specular reflections of sunlight (flat white paint is a good scheme). Furthermore, ranging through the COAS can be facilitated if some visible features of the TGT (either structures or markings) are sized appropriately so as to subtend angles of 2" at 100 feet and at 30 feet (that's a true linear dimension of 3.5 feet and 1 foot, respectively); this is a desirable, but not required, feature.

Reflection characteristics of the TGT can be enhanced by use of reflective tape. Visibility out to 500 feet can be achieved.

Spartan radar cross section measurements
without corner reflectors



Spartan radar cross section measurements
with corner reflectors

Figure 3-30.- Effect of corner reflectors on radar cross section.

In terms of lighting, if the reflection of the TGT characteristics or Orbiter pointing is inadequate to provide visual cues at night (regarding TGT relative position, orientation, and grapple fixture location), then running lights are highly desirable, with the following characteristics:

- Capability exists for flight-crew on-off commanding.
- Lights are steady-state with intensity of 1.0 candlepower on the beam cone centerline, decreasing to 10 percent of maximum at $\pm 80^\circ$.
- If flashing lights are required (due to power limitations), the rate should be more than once per second.
- The optimum number of lights is eight (of equal brightness), located orthogonally with respect to target coordinate frame, with color coding as follows: port - red (two), starboard - green (two), and bottom - yellow (four).
- A minimum of two lights should be provided on spin-stabilized TGT's.

Radar reflectivity can be enhanced through the use of simple corner reflectors (fig. 3-30), which significantly increase the radar cross section of the target.

In terms of close-in radar TRK, a radar enhancement device (RED) can be used to prevent beam wandering over a TGT of large angular extent; this can reduce noise in the range and range rate measurements. At long ranges a RED can be expected to provide more distant radar tracking capability.

3.4 NAVIGATION

The task of NAV is to find out where one object is located and is moving, relative to a reference frame or another moving object. This section describes the use of the REL NAV SPEC, the theory of Orbiter SV management, and the stages through which onboard sensor data pass into SV knowledge.

3.4.1 REL NAV (SPEC 033)

Relative navigation (REL NAV) (fig. 3-31) is available in OPS 2. It provides the crew with relative state information and translational thrust monitor capability for the RNDZ, PROX OPS, and PL deployment/retrieval phases of the mission. It also provides data and controls for RNDZ NAV operations using the STRK, RR, and COAS. NAV filter controls are provided to allow manual control of NAV data from the STRK, RR, or COAS, depending on which are being used.

					000/HH:MM:SS			
RNDZ	NAV	ENA 1X	SV UPDATE					
KU ANT		ENA 2X	POS	XX.XX	AVG G ON	5X		
MEAS		ENA 3X	VEL	XX.XX	AVX	±XX.XX		
NAV					AVY	±XX.XX		
SV SEL	4	XXXX	RR	XXXX	AVZ	±XX.XX		
RNG	XXXX.XXX	RNG	XXXX.XXXS		AVTOT	XX'.XX		
R	±XXXX.XX	R	±XXXX.XXS		RESET	COMPNT 6		
0	XXX.XX	EL	±XXX.XS		TOT 7			
Y	±XX.XX	AZ	±XXX.XS		SV TRANSFER			
V	±XXX.X	WP	±XX.XS		FLTR	MINUS PROP		
MODE	XX:XX:XX	WR	±XX.XS		POS	XX.XX		
FILTER					VEL	XX.XX		
S TRK	12X	RR	13X	COAS	14X	FLTR	TO PROP	8X
STAT	XXXXXXXXXX	OFFSET	X	±X.X		PROP	TO FLTR	9X
	XXXX		Y	±X.X		ORB	TO TGT	10X
SLOW RATE	15X					TGT	TO ORB	11X
COVAR	REINIT	16X	MARK	HIST	EDIT OVRD			
	RESID	RATIO	ACPT	REJ	AUT	INH	FOR	
RNG	±XX.XX	X.X	XXX	XXXS	17X	18X	19X	
R	±XX.XX	X.X	XXX	XXXS	20X	21X	22X	
V/EL/Y	±X.XX	X.X	XXX	XXXS	23X	24X	25X	
H/AZ/X	±X.XX	X.X	XXX	XXXS				

Figure 3-31 - The REL NAV (SPEC 033) display.

Interaction with Orbiter DPS actions can affect REL NAV's processing, as specified in section 3.7.

The NAV data is used to update the Orbiter SV. However, FSW can conceivably be changed so sensor data would improve the TGT state instead of the Orbiter state, but not through a simple ITEM entry on the REL NAV display. The present design has an I-loaded flag that determines which state will be updated by the Kalman filter. This flag could only be changed in I-load, or by a G-MEM via crew input or by uplink.

Note: Although FLTR is the SPEC abbreviation of "FILTER," use of the abbreviation "FILT" is widespread in documentation with identical meaning.

3.4.1.1 Parameters

The RR determined relative state information includes the following (compare to generic RNDZ parameters in section 2.5 and RR-specific parameters in section 3.3.4):

- RNG: Line of sight range (kft) between the vehicles.*

- R-DOT: Range rate (ft/s); sign convention is positive opening, negative closing.*
Note: Both raw radar and NAV values are displayed for RNG and R-DOT.
- EL: Pitch position (elevation) of the radar antenna gimbal relative to its -Z null position ($\pm 90^\circ$); positive sense - antenna motion toward the +X Orbiter axis.*
- AZ: Roll position (azimuth) of the radar antenna gimbal relative to its -Z null position ($\pm 180^\circ$); positive sense - antenna motion toward -Y Orbiter axis.*
- ωP or EL-DOT: Pitch inertial angle rate (\pm mr/sec); positive sense - antenna motion toward the +X Orbiter axis (mr = milliradians).*
- ωR or AZ-DOT: Roll inertial angle rate (\pm mr/sec); positive sense - antenna motion toward the -Y Orbiter axis.*

*This radar information will be displayed whether or not RNDZ NAV is enabled, as long as there is a data path through FF3. The same data can also be seen on crew station panel A2. After the radar locks on to the TGT, there are still down arrows on the REL NAV display for a short period of time. This happens because the software is conducting a data good check on the radar data and until the discrete becomes GOOD the down arrows will remain. RR data may still be good enough for manual phase.

- θ - (Theta): The angle between the Orbiter V-bar and the UNIV PTG body vector (ignoring effects of deadbanding). If UNIV PTG is tracking the TGT with the -Z axis, θ is the elevation angle of the TGT with respect to the chaser V-bar.
- Y - The out-of-plane distance (kft). Positive sense is along negative angular momentum vector of the TGT, or to the right when heads up, facing forward. For posigrade orbits, this is south.
- Y-DOT - The out-of-plane rate (ft/s), same sense as Y.
- NODE - The MET time hh:mm:ss of the next nodal crossing between TGT and Orbiter. This is generally unusable with current flight software precisions since the Orbiter and TGT are always so close to being co-planar.

3.4.1.2 Processing

RNDZ NAV processes sensor data to update the SV and covariance matrix in OPS 2 under the following conditions:

- NAV is on a measurement processing cycle, which occurs every other 3.84-second cycle. This is, marks are incorporated every 8 seconds (two NAV processing cycles).

- b. Sensed acceleration (CONT ACC) for this cycle is $< 20,000 \mu\text{g}$ (i.e., no OMS burn in progress, since a single OMS burn gives about $34,000 \mu\text{g}$).
- c. Data are flagged good.
- d. Auto/Inhibit/Force (AIF) switch is not set to INH.
- e. Data residual passes the NAV residual edit test.
- f. If in MM 202, MEAS ENA is on.

Note: Even though both radar and STRK output data at a rate faster than it can be used by software, RNDZ NAV simply snapshots the data when it is needed; it does not average the values.

3.4.1.3 REL NAV SPEC Manipulation

All item entries may require up to 8 seconds for response to appear.

3.4.1.3.1 RNDZ NAV enable (Item 1).- This item is used to transition between the basic orbit NAV and RNDZ NAV. It is a flip-flop item and is inhibited on initial display call-up whenever entering OPS 2. An asterisk will appear when RNDZ NAV is enabled.

The PROP SV is created as a copy of the FLTR SV, and the FLTR SV is enabled for sensor data incorporation. During RNDZ NAV, the TGT SV and the Orbiter/TGT covariance matrix are also maintained (in addition to two Orbiter SV's) using preloaded acceleration models and external sensor data (STRK, RR, COAS), if available. In non-RNDZ NAV, only the Orbiter FLTR SV is maintained; the TGT SV is not propagated and no external sensor data are used to update the Orbiter SV. If RNDZ NAV is not enabled, the following parameters are blanked: RNG, R-DOT, θ , Y, and Y-DOT.

When RNDZ NAV is enabled, the COVAR MATRIX is also initialized along with the mark accept/reject counters. Enabling RNDZ NAV does not change previous values of the AIF flags, the sensor selected as angle source, and the KU ANT enable flag. See sections 4.1.6 and 3.7.3 for operational use of this feature.

Note: A TGT SV must be less than 15 hours old to allow enabling of RNDZ NAV.

3.4.1.3.2 Ku-band antenna enable function (Item 2).- Execution of Item 2 results in the GNC GPC's passing the GNC relative state, which is necessary for Ku-band antenna management, to the SM GPC. SM commands the antenna through MDM PL1. This tells the radar where to point to acquire the TGT. Recall that the RR is part of the Ku-band antenna system, and that this function is controlled by the SM OPS 2 GPC. Prior to RR acquisition of a TGT, this item must be enabled and a GNC I/O reset performed. When this item is selected, the antenna is pointed at the target, no matter what the RR MODE switch says. See section 3.3.4.1.

3.4.1.3.3 Sensor measurement enable (Item 3).- This item, MEAS ENA, is used to enable the RNDZ NAV software to use onboard sensor data (RR, STRK, COAS) to update the filtered SV in MM 202. Even with the AIF's (EDIT OVRD selection) set to AUTO (items 1, 17, 21, 23 selected), onboard sensor data are not utilized in MM 202 unless the MEAS ENA item is selected. Even then, external sensor measurements can only be incorporated in MM 202 NAV if the total sensed acceleration is less than a threshold value (currently 20,000 μg). When that threshold is reached, such as during an OMS burn, only the IMU data are used to update the Orbiter SV. This item is not applicable in MM 201, and an attempt to use it in MM 201 will result in an ILLEGAL ENTRY message. In MM 202, execution of Item 3 will cause an "*" to appear when the capability is enabled in the software. This may take up to 8 seconds to be initiated. Upon return to MM 201, MEAS ENA will be automatically disabled and the "*" will disappear.

Current (mid-1987) thinking is to leave MEAS ENA off when in MM 202, since presumably enough RR data has been obtained in the period leading up to MM 202 transition (approximately 8 minutes prior to Ti TIG) for a good TGT'ing solution. If MEAS ENA were set "on," additional RR marks would be taken during this period and would presumably be improving knowledge of the Orbiter-to-target relative state. However, the Orbiter is moving to a BURN ATT, which was computed when the MNVR was loaded (Item 22) on ORBIT MNVR EXEC. Lambert guidance takes over just prior to the time of ignition (TIG -15 seconds) and computes a "new improved" BURN ATT (based on these recent RR marks) which may significantly differ from the one issued earlier if the maneuver is small. The problem is that the crew has no way of quickly (in several seconds) determining if this BURN ATT update truly reflects a genuinely improved knowledge of the SV, or is due to some guidance or tracking anomaly.

If RR acquisition occurs sufficiently in advance of the pre-Ti MM 202 transition, the small additional improvement potentially generated by more RR marks during maneuver to BURN ATT is considered to be insufficient justification for risking the dilemma of a sudden "surprise" at TIG -15 seconds. If RR lock-on is late and only a few marks are available for Ti targeting, the issue is more debatable. One possible way out is to then have MEAS ENA on during the maneuver to attitude and then reload the MNVR in ORBIT MNVR EXEC. Any change to BURN ATT will then show up with 1 to 2 minutes for decision, rather than 5 to 10 seconds. This issue is still being worked and final discussions will be reflected in specific mission RNDZ books.

3.4.1.3.4 State vector select (Item 4).- Item 4 allows the crew to control the source of the Orbiter SV for use in relative state data being displayed on REL NAV, and being sent to UNIV PTG, targeting, on-orbit guidance, and downlink to the MCC real-time monitoring. Item 4 is a flip-flop that alternately selects "filtered" or "propagated" Orbiter SV data. Upon execution, the word "FLTR" or "PROP," as applicable, will be displayed to the right of the item number. This item is initialized in "PROP." The filtered SV is an SV that incorporates RNDZ NAV filter data derived from RR, STRK, or COAS measurements. The propagated SV is a separate Orbiter SV which is not updated by RNDZ NAV filter inputs. The philosophy for practical SV management is described in section 3.4.2, plus in 4.1.14 and 4.1.22.

3.4.1.3.5 State vector update.- This section of the display shows the filtered SV correction in position (POS) and velocity (VEL) resulting from use of sensor data from the previous cycle. This is used to evaluate convergence of the filtered NAV state, particularly early in a sensor pass.

3.4.1.3.6 Powered flight NAV controls and displays (Items 5, 6, 7).- The upper right-hand portion of the display includes displays and controls useful during powered flight. In particular, item 5 is used to enable/disable the interface between Orbiter NAV and IMU-accumulated sensed-velocity data; nominal condition is interface enabled. In the nominal modes the NAV software continuously monitors the IMU accumulated sensed-velocity data and incorporates it if the observed ΔV exceeds a threshold value. AVG G comes up "on" in MM 201, but it may be toggled with ITEM 5 EXEC; AVG G is always "on" in MM 202 and ITEM 5 EXEC will result in an ILLEGAL entry message.

When AVG G is off, IMU-sensed velocities are not used in updating the Orbiter SV. With this type of modeling, RCS translations or rotations made manually by a crewmember with the THC or RHC will not be accounted for in the navigational model until observed with the on-board NAV sensors. Thus, before any such MNVR is made in MM 201, AVG G should be on.

In the upper right-hand portion of the display, a translation thrust monitor capability is possible when AVG G is enabled. The velocity gained along each of the X, Y, and Z body component axis, as well as the total velocity gained, will be displayed. The individual velocity component registers will increment or decrement according to the sense of the velocity change, whereas the total velocity will increment due to the absolute magnitude of any velocity change. An item number is provided (Item 6) to reset all of the component registers to zero, and another item number (Item 7) is used to reset the total velocity register to zero. The first time in OPS 2 that this display is called, these values will be zeroed. Thereafter, they will reflect the values which were available the last time the display was terminated (that is, the values become static when AVG G is OFF).

Current planning is for the AVG G switch to always be on. Experience has shown that the displayed velocity deltas are not particularly useful over a long period of time because of IMU noise accumulation. The only known reason to turn AVG G off would be if a new GPC IPL is required and GNC has been unable to uplink IMU accel compensations. The AVG G switch would be set to off until GNC has had a chance to do the IMU uplinks. There are no other known situations.

Note: There is currently a question of what the AVG G threshold value should be. The problem is to have a value high enough to eliminate accelerometer bias from being accepted by NAV, yet low enough to include all the uncoupled ROT maneuvers which affect the SV. It appears (minutes of Rendezvous Flight Techniques Panel 5, Sept. 9, 1983) that a threshold of less than 0.1 ft/s will be needed to detect 0.2 deg/s vernier RCS MNVR's which cause translation cross-coupling. The current IMU accelerometer 1-sigma bias is 50 μ g's (0.0016 ft/s/sec) corresponding to 0.01 ft/s over one NAV cycle (7.3 sec). This question is still being worked. Current limit is set to 0.06, a

"best compromise." IMU LSB allows pulses as low as 0.0345 ft/s to be measured.

3.4.1.3.7 State vector transfer (Items 8, 9, 10, 11).- Four item controls are provided for the transfer of SV's. Item 8 transfers the filtered Orbiter SV to the propagated Orbiter SV slots, and item 9 transfers the propagated Orbiter SV to the filtered Orbiter SV slots (this is called "FLTR RESTART"). FLTR to PROP occurs for several different rationales which are explained in detail in section 3.4.2.2.

Item 10 transfers the Orbiter FLTR SV to the TGT SV slots, and item 11 transfers the TGT SV to the Orbiter FLTR SV slot.

If a TGT TO ORB SV transfer (which replaces the FLTR SV) were done inadvertently, an easy, though not perfect, recovery would be to do a PROP TO FLTR SV transfer. The problem arises when an inadvertent ORB TO TGT state transfer is executed. Supposedly, the MCC plans to have a TGT SV ready for uplink at every AOS just in case something like this happens. The only other alternative is to keep repeating a COVAR REINIT followed by a few forced marks until data is accepted automatically.

Whenever any of the four transfer items are executed, an asterisk (*) will be displayed next to the appropriate item number while the selected transfer is in progress. The appearance and removal of the asterisk (*) will have a time delay depending on the NAV processing rate (the asterisk is displayed for only one NAV cycle). Items 8, 9, 10, and 11 are mutually exclusive; execution of any of these items while a transfer is in progress will be illegal. In addition, these four items are legal only while RNDZ NAV is enabled ("*" displayed by Item 1).

FLTR→PROP (Item 8) is nominally performed just after the beginning of each sensor acquisition period, and is a means of providing an up-to-date backup SV if for some reason the FLTR state wanders off (e.g., lock onto a star or debris). It is performed at this time because it appears that the Orbiter FLTR SV is good enough to attain acquisition.

PROP→FLTR (Item 9) is for contingency use, presumably in a situation such as just described where the FLTR state diverges and a FLTR SV restart is required.

ORB→TGT (Item 10) is primarily designed to provide an SV for deployed payloads, particularly nonimpulsive deployments such as via RMS (see section 5.4.1.4). TGT→ORB (Item 11) is provided for use after RNDZ completion. At that time it is quite possible that the TGT state will be more accurately known than the ORB state (currently, there is no planned utilization of this option). Note that items 9, 10, and 11 also cause a COVAR REINIT (see item 16).

Two parameters, FLTR MINUS PROP POS and VEL, indicate the difference between the propagated and filtered SV's. The FLTR MINUS PROP position value (in kft) can be used to evaluate how much the Orbiter FLTR SV has changed during a sensor pass. This assessment is particularly meaningful if data problems

were observed during the sensor pass. The POS and VEL values can be used to verify a successful FLTR TO PROP SV transfer; they should drop to zero. The VEL value is computed incorrectly and should be disregarded.

3.4.1.3.8 RNDZ NAV FILTER (Items 12 to 25).- Data from the RR, STRK, or COAS must pass a NAV filter residual edit test before it can be used to update NAV (the Orbiter SV and target/Orbiter covariance matrix). In the bottom third of this display, the results of this filter test and some crew controls are located. This allows the crew to monitor the condition of the filter and the external sensor measurements. In particular, the RR range and range rate residual edit test results are displayed, as well as the results for the selected sensor angle data (STRK-V/H; RR-EL/AZ; COAS-Y/X).

3.4.1.3.9 RNDZ angle sensor data selection (Items 12, 13, 14).- While RNDZ NAV is enabled with Item 1, the following external sensor data may be processed: RR elevation, azimuth, range and range rate, STRK horizontal and vertical angles, and COAS horizontal and vertical angles. The RR range and range rate are always processed by NAV as long as the RR DATA GOOD flag indicates valid data. However, only one of STRK, RR, or COAS will be used as a source of angle data as selected by the crew via items 12, 13, or 14, respectively. These are mutually exclusive items. Once again, a DATA GOOD flag for the selected external sensor must be "on" and residual edit test must be passed in order to be used in NAV. Also, the sensor must be in the appropriate mode. In particular, the RR must not be in a self-test mode, the STRK must be in the TGT track mode, and the COAS data (with COAS sight mode selected) must not have been previously processed and must not be stale (age exceeding 2 minutes) to be usable.

The display is initialized with STRK angle data selected (Item 12). When a new angle source is selected, a delay of up to 8 seconds will be experienced before the asterisk switches to the new source.

Note: When taking radar, STRK, or COAS marks, the software does not always take into account the sensor location relative to the Orbiter c.g. It does so only for the radar. Although data displayed on the CRT and LED's is based on position relative to the radar dish, they are converted to an Orbiter c.g. reference frame before being incorporated into the FLTR state. Thus, radar residuals and ratios are displayed based on the c.g. frame. On the other hand, STRK and COAS residuals and ratios are based on the location of the sensor; data is not converted to the c.g. reference frame before updating the FLTR state.

Also included in the RNDZ angle sensor select section is information used to monitor STRK operation. The STRK/COAS CNTL display is used to select which STRK (-Y or -Z) is to be in the TGT track mode. The status of the selected STRK will be displayed below Item 12, and can be one of the following: (blank), STRK FAIL, STRK PASS, NO TARGET, OUT FOV, or HI RATE (FALSE TRK was called for in the original design, but was not implemented). Below this status, a BITE indication can be driven when a failure has been detected for the selected STRK.

If the -Z STRK is being used, the offset angles (see section 3.3.3 for an explanation of COAS angles X and Y coordinate system) that represent the displacement of the TGT being tracked (by the -Z STRK) in the -Z COAS field of view will appear. These offset angles allow the crewman to locate the TGT that the -Z STRK is TRK in the COAS. This field is driven whenever there is a star present in the -Z STRK and the STRK is in target track or star track mode. It is updated every 1 second; the values are static when the STRK is searching.

3.4.1.3.10 NAV rates (SLOW RATE, Item 15).- The SV is updated in NAV at one of two rates. Current I-loads for slow and fast rate have been set identical, at 8 seconds per cycle, the fastest rate at which NAV can process STRK marks. Item 15 is a flip-flop item which can be used to select the desired rate, if future I-loads are no longer set to the same value. The first time the display is called in OPS 2, the asterisk will be present. If RNDZ NAV is not enabled, execution of this item is illegal.

3.4.1.3.11 COVAR REINIT (Item 16).- This will reinitialize the covariance matrix to preset I-load values or, if one or more covariance uplinks has been executed in the MCC, to the latest set of uplinked values. When the covariance matrix reinitializes, it resets differently depending on which angle sensor is selected, because it has different biases for each sensor. An "*" is displayed next to this item while the reinitialization is occurring. If RNDZ NAV is not enabled, this is an illegal entry. This is executed only as a contingency operation.

A covariance matrix is uplinked from the MCC, once before RNDZ phase and then again post-Ti with narrower limits (if acquisition by RR has occurred). There are six other ways the covariance matrix can be reinitialized besides this manual item entry, and they are listed in the "Mark History" paragraph, below.

COVAR REINIT is used when a sensor is apparently locked on to the TGT, but ratios are >1.0 so the marks won't get into the filter. Performing an "ITEM 16" will reopen up the filter (assuming that previous sensor marks have been taken; in cases when no sensor data has been taken in a long time, the matrix may actually get smaller) and reduce the ratios (if this does not work, the next step is to force a few marks). See section 3.4.1.3.13 for an explanation of edit ratios.

COVAR REINIT can be used to assist data incorporation when the Orbiter and target SV's are incorrect. Suppose the crew accidentally executes an ITEM 10 (ORB TO TGT transfer). If the Orbiter is less than a couple of miles from the TGT, the covariance matrix will accept radar data and converge on a fairly accurate relative Orbiter and TGT state even though the Orbiter SV will be wrong. Once converged, Lambert targeting (SPEC 34) could be used to compute a burn solution. At large separation distances, a COVAR REINIT may not be enough, so 1 or 2 marks may have to be forced until $RATIO < 1.0$ is satisfied and marks can be taken automatically.

3.4.1.3.12 Residuals.- A residual is calculated by taking the difference between the NAV computed estimate of the relative position of the Orbiter

and TGT, and the observed measurement using sensor data (STRK, RR, COAS). If RNDZ NAV is enabled and sensor(s) are correctly configured and are tracking the TGT, the residuals are computed and displayed for RR range and range rate, and for the selected sensor angle data (V/EL/Y, H/AZ/X). These data are blanked when RNDZ NAV is inhibited; if data are missing or invalid, the data remains static.

Angle residuals are monitored by the crew for approximately 30 seconds at the beginning of each TGT acquisition to ensure that the sensor is not locked onto a star or debris. The sensor is left in INH until the stability criteria is met.

The coordinate system of the angle residuals displayed in the V/EL/Y and H/AZ/X lines is confusing. The three labels are intended to correspond to the three angle sensors (STRK, RR, COAS respectively) and their inconsistent coordinate system references make it difficult to associate the residuals with any reference. See figure 3-11. In practice it is not necessary for the crew to appreciate the distinction between the two angles.

On the -Z STRK: the V/EL/Y line is "V" and means "azimuth" (related to the slightly tilted -Z STRK boresight), positive V toward the -Y wing; the H/AZ/X is "H," corresponding to elevation angle, positive H towards the nose (+X). In this sense the X and Y designations in the same line do actually closely correspond to the X, Y offset coordinates of the COAS (+X toward nose, +Y to left when facing aft, matching Orbiter body axes). It is important to note that the sign of the V (or azimuth) residual and the Y offset coordinate are opposite.

For the -Y STRK, V/EL/Y is "azimuth" from the -Y STRK boresight (approximately 11° toward nose from pure -Y), positive toward +X axis (nose), and H/AZ/X is "elevation" from out the -Y STRK boresight to the -Z axis (positive) or +Z axis (negative).

The COAS offset angles will be displayed any time the -Z tracker star present discrete is set. This discrete will be driven by a star or the TGT when the tracker is in STAR TRK or TGT TRK.

For RR, EL and AZ (or "roll and pitch") are not body axis elevation and azimuth (which is what EL and AZ mean in the RR section of the display in the upper center area). They correspond instead to physical antenna pointing angles, the trunnion (beta) and shaft (alpha) angle residuals (see fig. 3-15). As such they are hard to relate to the real body axes (to convert body axis frame to antenna frame, rotate the X axis about the Z axis to the right (+X into +Y) by 67°).

For the -Z COAS NAV data source option, EL and AZ are reverse of what they seemed for the STRK (see fig. 3-14). V/EL/Y is elevation in the COAS (in the COAS frame this is the X coordinate) and H/AZ/X is the azimuth (in the COAS frame this is the Y coordinate). The Y and X in the display text were originally named because the measurements are rotations about the Y and X axes.

For X COAS angles the residual V/EL/Y is measured in the XZ body plane with a positive measurement from +X towards +Z (an angle of depression). The residual H/AZ/X would actually correspond to a residual of azimuth angles since positive is measured from +X to +Y (nose to right wing). Thus if a perfect mark was taken and the COAS was perfectly aligned with the +X body axis then a positive V/EL/Y residual would indicate the TGT estimated LOS is above the true LOS and a positive H/AZ/X would indicate the estimated LOS is to the left wing side of the true LOS. If the radar is locked on simultaneously with X COAS tracking, then $EL = 23^\circ \pm E$ and $AZ = -90^\circ \pm S$ where E and S are functions of noise and bias in the radar system.

3.4.1.3.13 Residual edit ratio.- The residual edit ratio is the ratio of the magnitude of the actual measurement residual divided by a multiple of the expected residual based on the current covariance matrix. The residual edit ratio is computed for use in the data edit test inside NAV. A data measurement is edited if its residual ratio is greater than 1. The ratios update on the display in an 8-second cycle. See also 3.4.1.3.11.

In calculating a RATIO on the REL NAV display, the RNDZ NAV filter uses a value that is 6 times the expected error (covariance matrix and filter weighting). For example, the current covariance (which contains 1-sigma NAV uncertainties) starts at 20 kft in X. After a COVAR REINIT, a RATIO of 1.0 would reflect an error of 120 kft.

3.4.1.3.14 Mark history, accept/reject.- The number of NAV marks of each type (range, range rate, angle 1, angle 2) that have been accepted or rejected by the RNDZ NAV filter will be displayed.

These ACC/REJ counters are all reset to zero under the following conditions:

- a. After a burn (probably OMS) of more than 20,000 μg
- b. After covariance matrix reinitialization, either by execution of item 16 or by other actions as follows:
 - (1) Entering RNDZ phase (RNDZ NAV set to "*")
 - (2) Orbiter SV uplink during RNDZ phase
 - (3) Target SV uplink during RNDZ phase
 - (4) PROP + FLTR SV transfer
 - (5) ORB + TGT SV transfer
 - (6) TGT + ORB SV transfer
- c. When the angles input data source (STRK, RR, COAS) is changed (angle counters only)

When more than a K-loaded number (currently 3) of sequential marks are rejected, a down arrow will be driven in the status column of that measure-

ment type, an alert message ("NAV EDIT") will appear and a tone will be heard.

This down arrow is removed when the data are manually forced and the ratio test is passed for one mark, or when more than a K-loaded number (currently 2) of sequential acceptable marks occur.

3.4.1.3.15 AIF switch (EDIT OVRD - AUT/INH/FOR, Items 17-25).- The displayed residuals, ratios, accept, and reject counters serve as the basis for the crew decision as to how external measurement data are to be processed by the NAV filter. Three mutually exclusive options are available to the crew for each of the range (Items 17, 18, 19), range rate (Items 20, 21, 22), and selected sensor angle data (Items 23, 24, 25). These are as follows:

- a. AUTO: Valid sensor data passing the residual edit test are to be automatically used to update the SV and covariance matrix.
- b. INHIBIT: Valid sensor data are to be used for computing residual and ratio values but are not to be used to update the SV and covariance matrix. Thus, when in INHIBIT, the ACCEPT/REJECT counters will not be incremented.
- c. FORCE: The edit test criterion is relaxed, since the maximum allowable residual ratio used in the NAV filter edit test is increased to a higher value (currently last mark + 0.2). Valid data will be used to update the SV and covariance matrix only if the new edit criterion is met on the next residual edit test. These new test criteria are in effect for only one NAV cycle. The control then reverts to the previously selected option (AUT or INH). An "*" appears beside the FORCE item only while the control is in effect. For angles from COAS, the force option is the nominal mode for processing the data. The force input applies to the last COAS mark taken within the previous 2 minutes. However, NAV does not necessarily incorporate the COAS mark since it still could fail the ratio test, but this is not likely.

Note: When forcing COAS marks on the REL NAV display, the threshold (last RATIO value plus 0.2) is applied to the last forced and accepted mark, not to the last mark taken by pushing the ATT REF button.

When the display is first called in OPS 2, the INHIBIT items will be selected. These items are applicable both when RNDZ NAV is enabled in MM 201, and also in MM 202 when the MEAS ENA item is selected.

For all tracking passes, measurement incorporation will be inhibited prior to sensor acquisition. Inhibiting data prior to sensor acquisition allows the crew to assess the quality of the sensor data prior to its incorporation into the filter.

Note that the documented error message FALSE TRK will never appear on the display. The discrete that drives the message is used to update the reject

counter instead of displaying the message FALSE TRK. A problem incident report DR was written against the software, but instead of fixing the discrepancy, the requirement has been waived.

3.4.1.4 Editing Contingencies

The AIF switches on REL NAV are used to control flow of data from sensors into NAV. For all sensor acquisition intervals, measurement processing will be inhibited until the crew determines that the sensor acquisition was successful. At that time the crew will select AUTO, and NAV will begin to process the sensor data to update the Orbiter SV.

3.4.1.4.1 STRK Marks.- For STRK acquisition, there is a same risk that the STRK will lock-on to a star instead of the target, so the crew must monitor residuals and residual ratios for at least four consecutive NAV cycles. They should then select AUTO when residual growth is less than 0.05° for four measurement processing cycles and residual ratios are less than 1. If the residuals indicate TGT lock-on, but the ratios remain greater than 1, perform the following steps sequentially until the ratio drops below 1, then proceed with the timeline.

- a. Break track and reacquire TGT. If residual editing continuously occurs, most likely the STRK has either locked onto a star, or has a malfunction, or very large relative state errors are present. To prevent bad measurements from being incorporated into the filter, breaking lock and reacquiring the TGT is the desirable first step because it does not update anything in the relative navigation state.
- b. Reinitialize covariance matrix. If the covariance matrix has been reduced by measurement incorporation, reinitializing the covariance will expand it and allow larger updates to be incorporated into the filter (i.e., it enlarges the acceptance criteria). Incorporating these larger updates should correct the relative SV, which will stop the residual editing.
- c. Force up to three measurements (select AIF = FORCE for three marks). If covariance reinitialization is not sufficient to prevent residual editing, data can be forced into the filter (this enlarges the acceptance criteria still further). Three consecutive measurements should correct the relative SV sufficiently to stop the residual editing. If measurements continue to be edited, a generic problem may exist and, most likely, forcing more measurements will not improve the situation.
- d. Filter restart (propagated to filtered SV transfer). This assumes an unusable totally ruined FLTR SV. An SV restart eliminates all data incorporated into the filtered SV since the last filtered-to-propagated SV transfer. This is a last-resort procedure to correct the RNDZ NAV relative state.

At the end of the STRK pass, and before sunset, it is required that the STRK angles be set to INH in REL NAV to prevent the corruption of the FLTR SV if the STRK locks on to a star.

3.4.1.4.2 RR Marks.- For RR acquisition, the crew must monitor the radar data flags to verify no down arrows and verify that ratios are less than 1. Under these conditions, they would select AUTO. If after repeated RR acquisitions the ratios remain greater than 1, the following steps should be performed sequentially until the ratio drops below 1 (at that point, proceed with the timeline).

- a. Reinitialize covariance matrix. (See b. above.)
- b. Perform FLTR-to-PROP SV transfer. By this point the NCC burn has been performed, based on multiple STRK passes. If the onboard-targeted ΔV was within 3 sigma of the ground solution, this should validate the FLTR SV and it should be saved.
- c. Either select AIF = FORCE three times (to force three marks), which is the primary method, or wait for STRK data post-Ti to help resolve the impasse. If the FLTR SV has given a reasonable targeting solution for the NCC burn, perform FORCE. If FORCE is unsuccessful in that the RR data cause the FLTR SV to diverge, execute a filter restart (PROP TO FLTR) and then wait for the post-Ti STRK data.

3.4.1.4.3 RR/STRK Marks.- Post-Ti the crew will have both STRK and RR data available. Approaching Ti, the following procedure is used:

- a. Initial condition is ANG SELECT = RADAR and all AIF = AUTO.
- b. To perform Ti, go to MM 202, select ANG AIF = INH, perform burn, return to MM 201, when back in attitude select ANG AIF = AUTO.

3.4.1.4.4 COAS Marks.- A discussion of COAS marks is found in sections 3.3.3.3, 4.1.14, and 4.3.3.

3.4.1.5 Defining The Stages of Relative Navigation

The process of acquiring and utilizing onboard sensor data consists of several distinct events and criteria, each of which have been discussed individually elsewhere. A summary review of these events in proper sequence can allow an appreciation of their interrelationships, and can provide a view of the precise stages through which relative navigation progresses. The precise meaning of each of these stages is summarized below.

3.4.1.5.1 Search.- The STRK and/or RR sensors perform their programmed search patterns, or the crewmember looks through the COAS or on the CCTV monitor.

3.4.1.5.2 Detection.- The presence of the target is reflected by sensor monitoring software, but "DATA GOOD" flags are not yet set. Alternately, the target is spotted visually or on CCTV.

3.4.1.5.3 Acquisition.- "Data Good" flags are set on the RR parameters by the Ku-band hardware, and these are displayed; "S PRES" is displayed for the STRK. For STRK, see section 3.3.2.1; for RR, see section 3.3.4.5 and 4.1.30. For COAS, the equivalent phase is performed manually, with the crewmember noting the LOS angles.

3.4.1.5.4 Lock-on.- This implies that the sensor is performing closed-loop tracking with sensor data, aiming the sensor or the Orbiter based on this data. Only the RR and STRK are capable of "lock-on", and nominally they lock on as soon as they acquire.

There are RR configurations in which acquisition is not followed by lock-on but in which range and range rate marks may be used by relative navigation. Angle data should remain inhibited.

The COAS inherently cannot perform "lock-on", although with man-in-the-loop operation this function can be approximated.

3.4.1.5.5 Data into REL NAV.- This happens as soon as RR "DATA GOOD" flags are set, as long as the data path from sensor to GN&C GPC's is good. Sensor data is being processed by SPEC 33 for display purposes only, and RESID's and RATIO's (defined in 3.4.1.3.12 and 13) are being computed and displayed/downlinked.

3.4.1.5.6 Data meets "accept" criteria.- Data as displayed on REL NAV passes the RATIO/RESID editing criteria, as defined in navigation blocks in RNDZ BOOK. For STRK, see section 4.1.13; for RR, see sections 4.1.31 and 4.1.32.

3.4.1.5.7 AIF to "AUTO" (or "FORCE").- The crew manually modes AIF flags to "AUTO" (section 3.4.1.3.15) for incorporating sensor data into the GN&C navigation FSW computations to improve the FLTR SV. The ACC/REJ counters increment. Edit checking begins.

For COAS NAV, the marks are taken with the ADI REF pb, have their RESID/RATIO's displayed, and are then always individually incorporated into REL NAV by use of the AIF "FORCE" option.

3.4.1.5.8 Marks pass edit check.- The RESID's of each parameter meet edit criteria as defined by COVAR matrix (section 3.4.1.3.11). RR marks are converted from a sensor-centered to an Orbiter-cg-centered frame; STRK and COAS marks are not converted. They then are used to shrink the COVAR matrix and to improve the FLTR SV.

The commonly-used phrases "RR NAV" and "STRK NAV" refer to this stage. The "Sensor data" criterion used in Flight Rules also is best defined by this stage.

3.4.1.5.9 NAV converged (operationally).- In practice, for STRK, 40 marks will give "operational convergence". Other criteria include the SV POS update being less than 0.5 kft for the last four marks, or in general "SV POS/VEL updates small and stable".

This situation means that the FLTR SV is "good enough" for performing targeting: "good enough" is defined by the predictable errors being less than dispersions to be expected from other sources such as IMU errors or burn trim uncertainties. The FLTR solution will normally be better than either the PROP solution or the ground solution.

3.4.1.5.10 NAV converged (mathematically).- Additional marks continue to improve the FLTR SV and the accuracy of the FLTR solution, up to a point. After this point, the scatter of the NAV marks is such that no improvement in SV knowledge is made by incorporating further marks. For STRK, this occurs at about 120 marks.

3.4.1.5.11 End of tracking pass.- The sensor may be unable to continue taking marks (for STRK or COAS, at sunset; for RR, beyond a certain range or with a changed target attitude reducing its radar cross section). Generally, however, the tracking pass can end when the FLTR SV has fully profited from the marks and there is no advantage to taking more marks. At this point, the FLTR SV should be superior to the PROP SV. In practice, the sensor may be left locked-on to the target as long as feasible, but relative navigation is not the driver on this.

3.4.1.6 Improved REL NAV

Based on actual RNDZ mission experience, improvements to the REL NAV SPEC function have been developed and documented in CR 79735. These improvements may be implemented in the near future, once the new GPC's are installed on the Orbiter fleet. For the sake of future users, the following descriptive material outlines the expected new capabilities of REL NAV once the proposed improvements are in force. At that point, this entire section will be updated by a PCN to this book.

As outlined on the CR, the display changes include:

- a. Add arm/fire logic to RNDZ NAV ENA function. The "ITEM 1" will be the "ARM", and "ITEM 2" will cause execution of the RNDZ NAV state flip-flop. This will insulate the crew from inadvertently turning off RNDZ NAV and thus losing the current propagated state, which is serving as a backup SV. An inadvertent drop of RNDZ NAV complicates SV management plans.
- b. Modify thrust monitor computations of displayed ΔV 's. This will prevent incorporation of IMU noise, especially absolute values of same.
- c. Add display of PET (HH:MM:SS) and PROP SV (HH:MM:SS) age. The MET base time for the PET clock is entered on the TIME SPEC. The SV age clock is reset whenever the PROP SV is updated by uplink or item entry transfer.

This eases the crew mental timekeeping computation/comparison workload, allowing straightforward references to the FDF RNDZ Book and standard separation profiles.

- d. Add ARM/FIRE logic to SV transfer items. A special "ITEM 13" toggle is set prior to executing an ITEM 9, 10, 11, or 12 for all SV transfers. This will prevent inadvertent loss of one SV when the other is copied over it.
- e. Add accept/reject counter reset ITEM. This is ITEM 41 (RESET CNTR). It will give a quick count of marks during the current sensor pass, which is used as a cue to decide on "convergence."
- f. Add navigated elevation angle display. This is displayed both for FLTR-PROP and for currently-used SV (the angle between the projection of a line joining the Orbiter and the TGT into the orbit plane, and the Orbiter local horizontal plane, 0° to 360°). In addition, the angle between the projection of the Orbiter tracking body vector (selected on UP) into the orbit plane and the local horizontal (0° to 360°) is also displayed. This replaces a laborious manual crew task and aids in the plotting of Orbiter trajectory on "Relative Motion Plots" (section 4.7), which is valuable to alert crew to off-nominal dispersion trends.
- g. Change time OF nodal crossing (in MET) to time T0 nodal crossing (countdown in MM:SS). This is used as alert for imminent performance of out-of-plane-null burn post MCI, and relieves the crew from the requirement for constant monitoring and mentally estimating trends of Y and Y-DOT.
- h. Add STRK TGT present indicators. This is an easier feedback of status, and relieves crew of need to call up STRK/COAS SPEC repeatedly.
- i. Add COAS offset angles for RR. This allows visual observation through COAS of object being tracked by RR, especially if object is dim against star background.
- j. Modify display to show only the coordinate system for the RNDZ sensor which is supplying angle data. This enhances readability and reduces potential crew confusion.
- k. Delete filter slow-rate item. This is never used; originally it was intended to use STRK only every 16 seconds, to keep CPU time down.
- m. Add FLTR-PROP angle data. See "f", above.
- n. Expand RR status text field. This enhances readability and reduces potential of crew confusion.
- o. Blank residuals and ratios when data-good flag from sensor is off. This enhances readability and reduces distractions.

Further, the CR makes some changes to other displays. On the TIME DISPLAY, it adds PET SET controls and PET ALARM SET controls. On ORB TGT, it adds PET clock. On IMU ALIGN display, it provides crew control for updating the ΔV threshold as part of the thrust monitoring update to the REL NAV display.

3.4.2 State Vector Management

Three SV's are maintained aboard the Orbiter: The TGT SV, a filtered (sensor data) Orbiter SV (called FLTR), and a propagated Orbiter SV (called PROP) using IMU ΔV 's only. The management philosophy for the Orbiter SV has undergone considerable evolution due to SES experience, NAV analysis, RNDZ mission profile documentation development, and actual flight experience.

The crew is required to manage these SV's during various RNDZ mission phases by performing appropriate SV selection, transfers, and editing (AIF switches) via item entries on the REL NAV display (section 3.4.1).

3.4.2.1 State Vector Select

Upon entry into RNDZ phase (sections 4.1.6 and 4.1.14), the STATE VECTOR SELECT option is initialized to PROP. The setting will be manually changed to FLTR after 10 marks have been accepted by the filter for each measurement type appropriate for the active sensor, and when SV UPDATE POSITION is less than the following convergence criteria: for STRK, 1000 feet; for RR, 300 feet.

RNDZ burns are done using the most accurate SV. This will be the PROP state until the first good NAV sensor pass, then it will be the FLTR state. The PROP state then becomes a "backup" state, to be used if the FLTR state somehow becomes corrupted by bad data. See section 4.1.27 on "Solution Selection."

3.4.2.2 FLTR-TO-PROP Transfer

The crew will exercise a FLTR-TO-PROP SV transfer at the beginning of each new sensor tracking interval (excluding the first), to update the PROP SV with the up-to-date FLTR SV. The PROP vector will then be a better SV for any required future FLTR restart. The FLTR-TO-PROP transfer will not be exercised until after successful acquisition of the target with the tracking sensor (since if the acquisition is not successful, an independent Orbiter SV - the PROP SV - will be available to attempt acquisition again). Successful acquisition is regarded as confirmation of the goodness of the FLTR SV. Following acquisition, the crew will monitor the residuals, residual ratios, and sensor data-good for at least four NAV cycles (approximately 30 seconds) before executing the FLTR-TO-PROP transfer.

These FLTR-TO-PROP SV transfers will usually be conducted at the following times:

- a. After STRK acquisition (second pass), but prior to enabling the STRK data into the filter. Criteria are growth in residuals less than 0.05° over successive NAV cycles (every 8 seconds) and residual ratios less than 1. This is to save the current best estimate SV before putting sensor data into it, on the chance that the sensor data may subsequently degrade rather than improve the SV. A good practice is to keep a "proven SV" in the PROP slot for fall back in the event of FLTR SV problems (see section 4.1.22).
- b. After RR acquisition pre-Ti, but prior to enabling the radar data into the filter. Criteria are radar data flags good (no down arrow) and residual ratios less than 1 (see 4.1.31).
- c. Post-Ti, after the STRK or RR acquisition, but prior to enabling the data into the filter (section 4.1.45). Criteria are STRK angle residuals growth over about 30 seconds is less than 0.05° and all measurement residual ratios less than 1.

Caution: A FLTR-TO-PROP is generally not performed in the middle of a sensor pass because there is no positive test to determine if the FLTR SV is good.

3.5 TARGETING (SPEC 034)

Targeting is defined as the computation of the necessary MNVR required to transfer the Orbiter to a desired state or position at a desired time.

Rendezvous targeting begins with launch. During ascent the Orbiter is steered to the proper insertion orbital plane. This depends on the target's orbital plane and the phase angle at MECO. OMS2 is the first on-orbit rendezvous maneuver: it is a phasing maneuver targeted with the MCC rendezvous targeting processor (RTP). The MCC performs all rendezvous targeting until the range to the target decreases to about 200 n. mi., at which time onboard relative NAV sensors begin to measure the relative state more precisely than ground tracking of both vehicles.

Even within the last 200 miles, several maneuvers for phasing, altitude, and planar adjustment are targeted only on the ground. This is due to STS FSW algorithm limitations which were imposed in 1978 during a software scrub to make room for higher priority FSW. Only two-impulse rendezvous targeting software survived that scrub.

Before the 1978 scrub there were two separate onboard software packages which were expected to be incorporated into the FSW. One was a scrubbed-down version of the RTP which had Lambert 2-impulse maneuvers and coelliptic maneuvers; it also allowed a maneuver to be scheduled at geometric elevation angles, while transfer times between maneuvers could be scheduled in fractions of orbital periods or in minutes. The other package was the Prox

Ops Specialist Function which would perform CW targeting for terminal phase rendezvous (ranges < 5 n. mi.) since it was at that time just becoming evident that the Orbiter's FRCS was not large enough to support manual braking with the proposed double-coelliptic profile with a differential altitude of 10 n. mi.

During the scrub effort, essentially the Lambert 2-impulse scheme was extracted from the "onboard RTP" and placed into the Prox Ops Specialist Function, and the combination was renamed "ORBIT TARGETING" (SPEC 34). About 5 years later, the double coelliptic profile concept was dropped in favor of the stable orbit rendezvous (SOR) technique which solved the FRCS limitations.

While the "targeting" for PROX OPS is normally a manual function, performed by the crew with the aid of procedures which use raw sensor data and rules-of-thumb, most RNDZ translation MNVR's use Orbit targeting with AUTO maneuver execution (e.g., see sections 4.1.9 and 4.1.38).

The ORBIT TGT display is SPEC 34 and is available in GN&C OPS 2. (See figure 3-32.) This display and the associated orbit targeting software give the crew the capability to generate a software targeted two-MNVR set. The first MNVR is targeted to move the Orbiter from a predicted position to a desired TGT relative position in a given amount of time (ΔT). The second MNVR is targeted to null the Orbiter velocity relative to the TGT. The targeted MNVR outputs of this software are displayed to the crew on the ORBIT TGT SPEC are also available as inputs to the MNVR execution software and CRT display, ORBIT MNVR EXEC in MM 202. The ORBIT TGT display is divided into three sections: inputs, controls, and maneuvers.

One warning on MCC monitoring of onboard targeting activities: of all the parameters on the targeting SPEC, only "TGT ID" is currently downlisted. If the crew modifies a TGT set (deliberately or inadvertently), the MCC cannot see it. The MCC does not see PRED MATCH or BASE TIME.

3.5.1 General Description

In general, a sequence of RNDZ, braking, stationkeeping, or transition MNVR's can be performed by selecting the appropriate TGT set and executing the computation with the ORBIT TGT display, then executing the MNVR with the aid of the ORBIT MNVR EXEC display in MM 202 and repeating that procedure for each remaining MNVR in the sequence.

3.5.1.1 Target Sets

One of 40 targeting sets can be chosen by the crew via Item 1 on the ORBIT TGT display. The possible TGT sets are part of the I-load and may be changed by ground uplink or by crew manual input. In most cases, each TGT set has a nominal time (T_1) associated with it when the first MNVR should occur and the desired position, with respect to the target (ΔX , ΔY , ΔZ) where the Orbiter should be a given amount of time (ΔT) later. In this

case, the elevation of the TGT with respect to the Orbiter local horizontal is not usually used to determine T1. (Item 6 is zero.)

When the target set ID is entered in Item 1, the following will appear with data: Items 2-6, 17, 18, 19, 20.

These parameters are used by the targeting software to compute the first burn of the specified two-impulse MNVR sets. This computation is not made until a COMPUTE T1, Item 27, is executed. When the COMPUTE T1 item is executed, the other Items (7-12, 13-16) in the input list will be computed and displayed. Items 7-12 ($\Delta X/DNRNG$, ΔY , $\Delta Z/\Delta H$, ΔX , ΔY , ΔZ) show the Orbiter relative position (kft) and velocity (ft/s) with respect to the TGT-centered rotating curvilinear reference frame, at the input-time T1 based on current onboard NAV information. Items 13-16 (T2 TIG) represent the time of the second MNVR of the two-impulse set and are computed based on the T1 and TIG time and the given ΔT .

As will be described later, the computed ΔV 's (ΔV_X , ΔV_Y , ΔV_Z , total ΔV_T) necessary for the first burn will appear in the MNVR section of the display and will also be passed to the on-orbit guidance software (MM 202). The burn is not executed, however, until it is subsequently loaded with the ORBIT MNVR EXEC display. The burn is then executed (section 3.6.2) either automatically (OMS only) following a crew entry to the ORBIT MNVR EXEC display, or manually by the crewmember using the THC (RCS only).

```

2021/034/          ORBIT TGT          I 003/22:58:38
                                000/00:01:00
MNVR   TIG          AVX          AVY          AVZ          AVT
  2    3/22:59:38    + 20.1        9.6        + 4.2        + 22.7

INPUTS                                CONTROLS
  1 TGT NO                -2                T2 TO T1    25
  2 T1 TIG    3/22:59:38                LOAD        26
  6 EL                [-] 00.00                COMPUTE T1  27
  7  $\Delta X/DNRNG$  [-] 60.84                COMPUTE T2  28
  8  $\Delta Y$                 [-] 00
  9  $\Delta Z/\Delta H$         [+] 60.76
 10  $\Delta \dot{X}$                 [+] 85.24
 11  $\Delta \dot{Y}$                 [+]  9.56
 12  $\Delta \dot{Z}$                 [-]  5.37
 13 T2 TIG    4/00:00:01
 17  $\Delta T$                 - 62.0
 18  $\Delta X$                 [-] 21.22
 19  $\Delta Y$                 [+]  0.00
 20  $\Delta Z$                 [+] 60.76
 21 BASE TIME 3/21:22:52

```

Figure 3-32.- ORB TGT display.

Other options are available using this display. For example, with the elevation option, the T1 time is determined onboard and is the time when the TGT LOS is the specified number of degrees (Item 6) from the Orbiter local horizontal axis. This also resets the base time. As an example of another user option, if the input ΔT time (Item 17) is negative, a flag is set in the S/W such that a new T2 time will be computed with an algorithm which ensures that the second burn is accomplished in a direction orthogonal to the TGT LOS. This could be used in orthogonal braking. Current procedures do not use this option.

Another option includes user input of a T2-TIG in Items 13 to 16, with ΔT (ITEM 17) set equal to zero. Then the software will compute ΔT for the user. Finally, the user may input what he feels is the true relative state of T1 via Items 7 to 12. After these are subsequently loaded via Item 26, the software will utilize the "required relative state" to determine the ΔV maneuver when Item 27 is requested. As an example, if the crew used alternate ranging devices (e.g., ranging rulers) while stationkeeping on the V-BAR when the Ku-band radar has failed, they could load the resulting range into Item 7 and set Items 8 to 12 to zero. They could then compute a maneuver to transfer to the -R-BAR or some other point in some transfer time ΔT .

Current planning includes a midcourse burn (MC2, section 4.2.4.4) targeted on elevation, but no use of orthogonal braking (possibly with space station).

3.5.1.2 Targeting Computation Techniques

A detailed discussion of Lambert targeting versus Clohessy-Wiltshire (C-W) targeting is found in Appendix B of the Rendezvous/Proximity Operations workbook (February 1985). In practical terms, the following brief treatment explains the different procedural options available to the crew.

In MM 202, burns may be executed with either Lambert iterative guidance or with constant or external ΔV targets. The former must be targeted onboard, using the Lambert computation technique; the latter may be targeted onboard using the C-W computation technique, or the ΔV 's may be manually entered from written pads (see section 3.6.1). The choice of Lambert vs C-W targeting is specified in the MNVR table defined by I-load.

Computations for Lambert targeting were once expected to take much longer to solve, but that disadvantage never materialized and targeting now typically takes 10 to 30 seconds. Its advantages include dynamic retargeting in the event of a TIG slip. The only practical advantage of the C-W technique is its ability to handle multi-REV targeting, and that advantage is not needed for current RNDZ strategies. Hence the current policy is to perform all onboard targeting using Lambert guidance, while doing ground-targeted burns in "external ΔV " (PEG 7) mode.

3.5.2 Inputs to ORB Targeting

3.5.2.1 Target Number (Item 1)

As stated earlier, the capability exists to load 40 predefined MNVR's in the I-load preflight. These MNVR's may be changed through ground G-MEM writes, or by the crew through Items 2-20 and execution of a LOAD item (Item 26) on this display. For each TGT set there is a flag internal to the software which is set to identify whether Lambert targeting or the closed form Clohessy-Wiltshire equations will be used in the targeting. These flags are part of the I-load and can be changed by the ground or by the crew via GPC memory modification using the GPC MEMORY SPEC (There is no known reason for wanting to do this). The number entered with Item 1 will retrieve the necessary targeting inputs for that MNVR set from memory and display them in the appropriate locations on the display. An example of the projected TGT sets is given in figure 3-33. Other target sets are either blank C-W or blank Lambert, so they can be called up and filled in as specified by the MCC for off-nominal situations. Note that transitions out of OPS 2 will result in the reinitialization of the original I-loads upon subsequent return into OPS 2. In the following sections, assume that a TGT number has been entered in Item 1.

Target set ID	MNVR to be computed
9	NCC
10	Ti
11	MC1
12	MC2
13	MC3
14	MC4
19	MC2 on TIME

Figure 3-33.- Projected TGT sets.

3.5.2.2 T1 TIG (Item 2-5)

These items specify the time (days, hours, minutes, seconds) in MET of the first burn, in the 2-impulse pair. If the COMPUTE T1 item (Item 27) is executed when the T1 TIG is in the past (as may happen, if a burn is missed, or if it is recomputed due to high velocity residuals following the first execution of the burn), or is less than an I-loaded interval (currently 1 minute) in the future, a new T1 TIG will automatically be computed as the current time plus the predefined I-loaded interval (currently 1 minute) and the transfer time will be decremented accordingly. Also this will cause software to ignore any inputs in Items 7-12, and instead, the software will use the onboard navigated state at that new T1 TIG time. It is also possible to change the T1 TIG through a keyboard entry to Items 2-5. In this case, the word LOAD will flash next to Item 26, and after the input

values are verified, they will be loaded into the I-loaded slots for the T1 TIG for that TGT set after execution of Item 26.

The I-loaded T1 TIG times are actually loaded in the software as times referenced to the "base time" (Items 21-14). (See section 3.5.2.8). This was done to make it easy to slip a full RNDZ plan: just change the BASE TIME and all T1-TIG's will be adjusted accordingly.

3.5.2.3 Elevation Angle (EL-Item 6)

This item refers to the elevation angle, positive up, to the TGT. If the EL = 0, the elevation angle option is ignored and the input T1 TIG and associated values will be used. However, for certain MNVR's such as MC2, an elevation angle $\neq 0$ (such as 28°) will be loaded. When this is the case, the T1 TIG time is determined by the onboard software as the time nearest the T1 TIG time at which the elevation angle is equal to value given in Item 6.

The angle tolerance is approximately 0.3° . If ORB TGT cannot satisfy this tolerance, an SM class 3 alarm (EL ANG) is issued (see section 3.5.5).

For current RNDZ profiles, the MC2 burn is targeted on elevation (see section 4.1.51).

Note that the crewmember can change a TGT set based on elevation angle to one based on the TIG time by reloading an elevation angle of zero. Loading zero does not force an elevation search for 0° so it will use the specified TIG.

It is possible for a burn based on elevation not to set the BASE TIME equal to the T1 TIG time. This can happen when the TGT set is computed with an initial displayed T1 TIG time in the past. When the TGT set is computed the elevation angle will be ignored, but not removed from the display. The TIG will be 1 minute in the future and the ΔT will be decremented accordingly.

3.5.2.4 Relative Position Items (T1 $\Delta X/DNRNG$, ΔY , $\Delta Z/\Delta H$, $\Delta X-DOT$, $\Delta Y-DOT$, $\Delta Z-DOT$ - Items 7-12)

These items show the Orbiter relative position (kft) and velocity (ft/s) with respect to the TGT at the T1 TIG time. If they are all zeros, or if the T1 TIG time is in the past, all of their values will be computed and displayed based on the onboard NAV information at the time a COMPUTE T1 (Item 27) is executed.

Alternately, values can be manually entered for Items 7-12 which will be used in the targeting algorithms as the assumed correct relative position and velocity of the Orbiter at the T1 TIG time regardless of the onboard NAV software. When one of Items 7-12 is entered, the LOAD item (Item 26) will flash until it is executed. Execution of this item actually loads the values in the INPUTS section of the display which are then used in the

computations (relative state keyed in, but not loaded, is completely ignored). This provides a means for overriding the NAV state, although this is not used in any nominal procedures. The crew can get back to the onboard vector by calling a new TGT set.

3.5.2.5 T2 TIG (Items 13-16)

This item represents the time in MET of the second MNVR of the two-impulse set. If ΔT (Item 17) is not zero, a COMPUTE T1 (Item 27) will cause the T2 TIG to be calculated and displayed. If the T2 TIG is in the past when a COMPUTE T2 is done, it will be reset to current time plus a predefined ΔT , and the MNVR is computed using the NAV state vector at the new T2 TIG time. A "COMPUTE T2" does not update items 7-12.

NOTE: If a TGT set is computed (ITEM 27) with a T1 TIG in the past, targeting won't still attempt to get to the T2 point in the ΔT specified in the TGT set. When the TGT set is computed, the T1 TIG will be changed to the present time plus 1 min. The ΔT will also change an equal amount to reflect time elapsed since the original T1 TIG. The T2 TIG will remain the same.

Undesirable results may follow if the crewmember tries to compute a burn with a TIG in the past greater than the ΔT in the TGT set. Because the time change is greater than the ΔT , a negative time change is seen as a request for orthogonal braking and the S/W will try to compute a solution accordingly. This may result in an iteration alarm, a lengthy computation time, and an erroneous solution.

3.5.2.6 Delta-T (Item 17)

The transfer time in minutes between the first MNVR time (T1 TIG) and the second MNVR time (T2 TIG) is represented by ΔT . If ΔT is zero, it will be computed based on the T2 and T1 TIG times when a COMPUTE T1 is executed. If ΔT is negative on execution of a COMPUTE T1, both ΔT and T2 TIG will be computed based on an algorithm used in orthogonal braking and will be displayed. The algorithm computes the ΔT (and thus the new T2 TIG) necessary to ensure that the second burn of the two-burn MNVR set occurs normal to the LOS from the Orbiter to the TGT.

3.5.2.7 T2 Relative Position (ΔX , ΔY , ΔZ - Items 18-20)

These parameters represent the desired Orbiter relative position (kft) at the T2 time (ΔT after T1 TIG - Items 13-16). This is the TGT position for the first COMPUTE T1. If a COMPUTE T2 is done, a burn will be computed that will null the relative velocity between the Orbiter and TGT at the T2 TIG time, regardless of these values.

3.5.2.8 Base Time (Items 21-24)

This is the time from which subsequent MNVR's are calculated. As was stated earlier, each MNVR time in each MNVR set is stored as a ΔT added to a base time. Thus, in general, an entire RNDZ can be slipped without adjusting T1 TIG times. The base time is originally an I-loaded value. It automatically changes when the elevation angle search option is enabled for a Lambert-targeted MNVR. It is reset to be that MNVR's computed T1 TIG time. Thus, the base time is updated to the MC2 time when the MC2 MNVR is computed based on an elevation search (this is the only burn currently targeted on elevation). This forces subsequent MNVR's to occur at times relative to the elevation angle time.

This time is defined in MET and is used to anchor onboard calculations for burn execution to a specific instant during the mission. The I-loaded set of burn parameters for the Orbit-targeting software includes only a relative time tag for each translational burn and requires a mission timeline-specific MET anchor. By using this scheme, the entire RNDZ profile can be moved to various times in the mission, and only the base time needs to be updated. The base time for ORB TGT has been defined to be the ignition time of the T1 burn, although any time would work as long as the appropriate relative time tags were loaded as part of the I-loaded burn parameter set.

In loading the base time the crew calls up TGT set number 1 before entering the data, because loading the base time can alter the I-loaded data set, and TGT set no. 1 is an unused blank data set. Calling up an unused TGT set when they change BASE TIME is for protection. When it is first called up, it displays TGT set zero. Changing any item in that TGT set will write it into an unpredictable memory location not allocated to the 40 TGT sets. Subsequently, calling up TGT set zero will result in an ILLEGAL ENTRY.

3.5.3 Controls

3.5.3.1 T2 to T1 (Item 25)

This item forces the T2 TIG time of the previous MNVR set to be transferred to the T1 TIG slot of the currently called MNVR set. This is useful, for example, in orthogonal braking where the ΔT and T2 TIG times for each MNVR are recomputed in order to ensure that the burn at T2 is normal to the TGT LOS. In this case, it is desirable to target the next two-impulse MNVR set with the new T1 MNVR TIG being at the previously defined T2 TIG. This is not currently used.

3.5.3.2 LOAD (Item 26)

Execution of this item loads item entry data values into the data slot for use by the targeting software. They actually overwrite the I-loaded values so that if that MNVR set is again requested via ITEM 1, the newly loaded values will appear. If any item entry (except TGT NO) in the INPUTS section

is made, the word LOAD flashes until Item 26 is executed. After it is executed, it will remain static until a new item is entered in the INPUT section.

3.5.3.3 COMPUTE T1 (Item 27)

Execution of this item results in the software calculating the first MNVR of the specified two-MNVR set. The calculated results are displayed in the MNVR section of the display and are also output to guidance for display on the ORBIT MNVR EXEC display. Also, all of the items in the INPUTS section of the display will fill in. An "*" will be driven beside Item 27 until the calculations are complete (7-10 seconds for both Lambert targeting and for C-W targeting). As soon as the T1 computation is complete, the GN&C CRT timer will start counting down to the T1 TIG (it is stopped by a MM 202 transition or a LOAD on MNVR EXEC, and must then be restarted).

A targeting computation during a burn execution is not ignored, but is held and executed immediately when the burn is completed (i.e., when TGO = 0). Therefore, the crew must not initiate an orbit targeting computation during a burn, or the burnout velocity-to-go (VGO) residuals on the MNVR EXEC display will be lost.

There are no reasons why a preliminary TGT solution cannot be computed while the Orbiter is maneuvering to a new attitude after the maneuver. In fact, loading the TGT set early gives the advantage of having the CRT timer start counting down to the burn sooner (e.g., post T_i, the preliminary MCI solution is called out to be calculated on the way back to track attitude).

3.5.3.4 COMPUTE T2 (Item 28)

This item is used to initiate the calculation of the second MNVR of the two-impulse set. This second MNVR is calculated to null the relative velocity at the T2 TIG. As stated earlier, if the T2 TIG is in the past, it will be updated to the current time plus a delta. An "*" is driven by Item 28 until the MNVR calculations are complete. When the calculations are complete, the required ΔV 's are displayed in the MNVR section of the display and are passed to guidance awaiting execution. Also, the GN&C CRT timer will start counting down to the T2 TIG.

Note that execution of an Item 28 (COMPUTE T2) while the computation for Item 27 is still in progress, and vice versa, is illegal, and an ILLEGAL ENTRY message will be generated if that is attempted.

If the crewmember calls up a TGT set and does a COMPUTE T2 before doing a COMPUTE T1, the software will calculate the ΔV required to null rates at the last computed T2 time, which was saved internally during the last MNVR computation. Therefore, a COMPUTE T1 must always be performed before performing a COMPUTE T2.

If the crewmember executes a COMPUTE T2 with a T2 TIG in the past, the new T2 TIG will be the present time plus 1 min. All relative rates at the T2 ignition point will be nulled out.

This compute option not currently used.

3.5.4 Predictor Match (PRED MATCH)

Predictor match gives the distance (in feet) to which the onboard orbit predictor was matched in targeting. In other words, this is a readout of the GNC GPC selfcheck of how well the targeting logic can compute the given MNVR. The GPC's will make 3 to 10 iterations in calculating the burn solution, and will stop iterating when a solution has a predictor match ≤ 250 feet or for elevation angle $\pm 0.30^\circ$ (it will always make at least 3 iterations). There is a practical relationship between a small value of predictor match and the quality of the solution. Failure to achieve these tolerance limits in ten iterations results in a fault message.

As a result of precise PROX OPS flying requirements on 51-F, the predictor match was set to 2 feet for that flight, and points were hit to within 30 to 50 feet (with the time between the maneuver and arrival at the desired offset point being 7 minutes). This distance was larger than 2 feet primarily because of maneuver trim residuals and onboard computer precision limitations affecting Lambert guidance and their error effects propagating through the 7 minutes.

Note: To perform such precise flying, another targeting constant, eps-mu (a tolerance inside of a second iteration), must also be changed (from E-6 to E-7).

3.5.5 Alarms

There are three SM alerts which can appear while using ORB TGT display (see also their impacts in section 3.5.9, items "g", "i", "j", and "k"). They are:

3.5.5.1 TGT ΔT

This occurs when software tries to compute a solution whose ΔT results in a transfer angle near 180° or 360° ("near" as defined by an I-loaded value, currently about ± 2 min or $\pm 8^\circ$), whose ΔT requires a parabolic transfer, around multirev transfer time singularities, or during an iteration failure in the orthogonal braking logic. The crew should check the transfer time and, if necessary, correct input errors. If using multirev capability, decrement ΔT by 10 minutes and retarget. If using orthogonal braking, override the option by reselecting the TGT set and removing the minus sign.

3.5.5.2 TGT-ITER

This can appear when using Lambert targeting. It can result when ORB TGT makes 10 iterations without reaching a solution. Crew should check PRED-MATCH and if it looks good, execute the MNVR anyway.

3.5.5.3 TGT EL ANG

This appears during Lambert targeting when the software exceeds the maximum number of iterations in planning a burn based on elevation angle, or when the desired elevation angle is not achievable. Targeting will indicate what angle the iteration stopped at by displaying it in ITEM 6. The ΔV 's displayed on ORBIT TGT pertain to the displayed angle. Crew should check displayed angle and if it's good enough, execute the MNVR.

If the displayed value is near the desired value, then it is likely that the failure was due to maximum iterations; in this case, it is possible to recall the TGT set and retarget. The iterations will then begin from the end of the last set of iterations and continue for 10 more iterations. If value is highly divergent, the burn should not be executed; instead, the crewmember should remove elevation angle and use preflight T1 (TGT SET 19).

Note: Display of this message is considered highly unlikely and is not expected to occur, even with any anticipated trajectory dispersions.

3.5.6 Maneuvers

This section identifies parameters for one of either of the two-impulse MNVR's which has been computed. A MNVR using COMPUTE T1 is that required to intercept the desired position in a desired time, and a MNVR using COMPUTE T2 is that required at the intercept time to null relative motion (as observed in a target-centered rotating curvilinear reference frame). Quantities displayed in this section for each MNVR include:

- a. XX - The target number on which the MNVR is based
- b. X - An indicator (*) that the TIG is in the past
- c. TIG - The impulsive ignition time (days, hours, minutes, seconds) in MET
- d. VX - The LVLH X-component of the targeted ΔV (ft/s)
- e. VY - The LVLH Y-component of the targeted ΔV (ft/s)
- f. VZ - The LVLH Z-component of the targeted ΔV (ft/s)
- g. VT - The magnitude of the targeted ΔV (ft/s)

Note that these solutions are not downlisted.

3.5.7 Out-Of-Plane Procedures

Out-of-plane dispersions are handled both by ORB TGT and later manually based on REL NAV. The ground-targeted NPC ("plane change") burn done early in the RNDZ phase removes out-of-plane dispersions observed via ground tracking. Onboard optical tracking pre-NCC provides additional relative orbital plane knowledge. This is used by ORB TGT for NCC targeting, to place T_i in plane. Subsequent T_i targeting (using post-NCC onboard radar tracking) places TGT intercept in plane, as well as can be done with these observations. In doing this, another node is created half a REV before intercept, and it is at this node that the RNDZ checklist calls for a manual plane correction to trim out all remaining out-of-plane error.

The theoretical background for out-of-plane control is given in section 2.9.2; the actual procedures are specified in 4.1.19 (Target NCC), 4.1.33 (Target T_i), and 4.1.54 (perform OOP null).

3.5.8 Operational Constraints

The orbit targeting software for flight software FSW version OI-7 still has several minor problems (see OI-7 Program Notes, JSC-19320, PN-OI7), as described below. The operational constraints they impose are as follows:

- a. An elevation angle search for an elevation angle which cannot be obtained may take more than 15 minutes to complete. The long computation time results from an incompatible elevation angle which cannot arise in normal operations. A large relative SV update prior to an orbit targeting elevation angle search could produce this problem, for example. The inconsistency with the requirements will be resolved by CR #69491B, approved for OI-11.
- b. An infinite software loop is possible when targeting Lambert MNVR's with a 180° transfer angle, but another coding error accidentally prevents the software from getting into the loop. A CR fix (#69133C) is approved for version OI-11. Such transfers are not planned for nominal RNDZ profiles.
- c. A precision problem exists in the elevation angle computation. The problem occurs only for small phase angles. For a ΔH of 1 n.mi., the elevation angle computation breaks down around 50° . This is not really a limitation, since the baselined RNDZ profile operates at about 28° elevation angle at a ΔH of 2 n. mi. (see section 4.1.51). CR #69491B has been written to correct the problem, and has been approved for OI-11.
- d. Upon initial call up of the ORB TGT display (SPEC 34) after entering OPS 2 from another OPS, the selected TGT set is initialized to 0. If a COMPUTE T1 (Item 27), or a LOAD (Item 26), or a COMPUTE T2 (Item 28) is then requested, undesirable results may occur. These include:
 1. Targeting may require several minutes to complete.

2. One or more GPC errors may occur.
3. Various targeting alarms may be annunciated.

Therefore, the crewmember should not request a COMPUTE T1 for TGT set 0 or when ΔT and T2 TIG are both zero. The crewmember must not request a LOAD for TGT set 0 (it could write zeroes into data locations not allocated to ORB TGTing). Any results displayed after performing any of these requests should be ignored. The orbit targeting protection CR #69491B adds protection to orbit targeting from operating on a non-existent (zero) TGT set; this CR has been written and approved for flight software version OI-11.

- e. Orbit targeting allows the crewmember to define the Orbiter state (at T1 TIG) for a Lambert MNVR in terms of a TGT state and a keyboard input target centered relative state. The targeting algorithm will compute a MNVR based on the input relative state and transfer the MNVR information to the ORBIT MNVR display. When load is executed for the ORBIT MNVR EXEC display, neither the ORB MNVR display nor on-orbit guidance has knowledge that an input relative state was used. Consequently, an Orbiter state (at T1 TIG) is generated based on the current Orbiter state from on-orbit user parameter processing. This situation results in a targeted MNVR different from the intended MNVR. The degree of difference in the MNVR's may or may not be observable when comparing orbit targeting display data against ORBIT MNVR exec display data, but in either case the resultant MNVR will not yield the expected results.

Because the difference between the computed MNVR and the desired MNVR may not be readily observable, it is recommended that the relative offset state targeting technique not be used in PROX OPS. If it is desired to use the technique, either of the following workarounds is recommended:

1. Use the C-W targeting algorithm rather than Lambert (see section 3.5.12); or
 2. Manually transfer the Lambert targeting data to the PEG 7 portion of the MNVR EXEC display and perform an external ΔV MNVR.
- f. The value displayed for T1 TIG (Item 2 on the orbit targeting display, SPEC 34) may be 1 second less than the actual value of TIG used by guidance after the following sequence is performed:
 1. The displayed TGT set data is stored into the predefined TGT set storage locations via an ORB TGT load (Item 26);
 2. That same TGT set is evoked again, via item 1. Note that an intervening compute T1 (Item 27) or compute T2 (Item 28) makes no difference.

If a compute T1 is then done, the value displayed for T2 TIG (Item 13) may be 1 second less than the actual value used by guidance. The CRT

be incorrect: VGO, TGO, total ΔV . The total ΔV will be in excess of 100 ft/s, with the VGO components and TGO correspondingly large. If the DAP is in AUTO mode, the Orbiter will maneuver to the incorrect burn attitude and maintain the incorrect body rates. Correct values for all of these parameters may be restored after four seconds.

The crewmember should terminate the burn immediately. If there is not enough time to set up and execute a corrective MNVR before the next scheduled MNVR, expect the next scheduled MNVR to be off nominal in order to correct for the aborted burn. If there is time to do a corrective MNVR, compute the corrective MNVR solution on the ORB TGT display using the same TGT set as for the aborted burn. To ensure successful execution of the corrective MNVR, the MNVR should be done using external ΔV guidance rather than Lambert guidance, although Lambert guidance may work. Beware of 180° and 360° transfer time singularities.

- k. If a compute T1 (Item 27) is requested for a Lambert TGT set and the "TGT ITER" or the "TGT ΔT " alarm is annunciated during the computation, the resultant MNVR solution will probably be incorrect. The VGO's displayed on the orbit TGT display are expected to be grossly in error, but they may appear reasonable when they are really are not. The resultant MNVR-solution computed solution is required to verify this. In addition, the ground may see multiple GPC errors during the computation.

The crewmember should not execute the resultant MNVR unless comparison with the ground solution indicates the solution is good. Otherwise, check that the input data for the TGT set is reasonable. Especially ensure that the transfer time does not yield a 180° or 360° transfer angle. If the input data is correct, recomputing the MNVR may produce a successful solution. If recomputation fails and a ground-computed MNVR is available, enter the ground-computed MNVR on the ORBIT MNVR EXEC display and execute. If out of contact with the ground, manually transfer the data to a CW TGT set and compute the MNVR solution using C-W targeting. Note that if the MNVR uses orthogonal braking, TGT data must also be transferred for the next TGT set as well.

3.6 CONTROL

Once a desired change in orbit has been defined targeting, it should be performed by "maneuver execution". This involves performing a propulsive burn to create a controlled ΔV .

3.6.1 PADS

Numerical data define MNVR's which can then be input to the MNVR EXECUTE display; this data is written on prepared forms called "BURN PADS", found in the RNDZ checklist. The burn data may be calculated several times (e.g., preflight, preliminary, intermediate, and/or final) and entered on the form

be incorrect: VGO, TGO, total ΔV . The total ΔV will be in excess of 100 ft/s, with the VGO components and TGO correspondingly large. If the DAP is in AUTO mode, the Orbiter will maneuver to the incorrect burn attitude and maintain the incorrect body rates. Correct values for all of these parameters may be restored after four seconds.

The crewmember should terminate the burn immediately. If there is not enough time to set up and execute a corrective MNVR before the next scheduled MNVR, expect the next scheduled MNVR to be off nominal in order to correct for the aborted burn. If there is time to do a corrective MNVR, compute the corrective MNVR solution on the ORB TGT display using the same TGT set as for the aborted burn. To ensure successful execution of the corrective MNVR, the MNVR should be done using external ΔV guidance rather than Lambert guidance, although Lambert guidance may work. Beware of 180° and 360° transfer time singularities.

- k. If a compute T1 (Item 27) is requested for a Lambert TGT set and the "TGT ITER" or the "TGT ΔT " alarm is annunciated during the computation, the resultant MNVR solution will probably be incorrect. The VGO's displayed on the orbit TGT display are expected to be grossly in error, but they may appear reasonable when they are really are not. The resultant MNVR-solution computed solution is required to verify this. In addition, the ground may see multiple GPC errors during the computation.

The crewmember should not execute the resultant MNVR unless comparison with the ground solution indicates the solution is good. Otherwise, check that the input data for the TGT set is reasonable. Especially ensure that the transfer time does not yield a 180° or 360° transfer angle. If the input data is correct, recomputing the MNVR may produce a successful solution. If recomputation fails and a ground-computed MNVR is available, enter the ground-computed MNVR on the ORBIT MNVR EXEC display and execute. If out of contact with the ground, manually transfer the data to a CW TGT set and compute the MNVR solution using C-W targeting. Note that if the MNVR uses orthogonal braking, TGT data must also be transferred for the next TGT set as well.

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3.6.1.2 Other Systems Data

Performance of a burn may involve systems reconfiguration, which can be specified either on a cue card or on the burn pad. For example: OMS gimbal check (left/right, primary/secondary, pre/postburn) may be specified; OMS HE regulator (A,B), both sides, may be set to GPC/OP/CL; RCS interconnect may be altered. In addition, systems reconfigurations which are associated not with the burn but with some activity which closely follows the burn, may also be specified (e.g., IMU deselect, which actually is associated with the subsequent STRK pass. See sections 3.3.2.1 and 3.9.4).

3.6.1.3 Ti Delay PAD

The Ti burn is a convenient point to stop the RNDZ for one or more REVs, if needed. Instead of burning the nominal Ti pad, the crew loads a special pad read-up from the MCC (fig. 3-35). Use of this pad is discussed in section 4.1.40 in the RNDZ procedures rationale narrative.

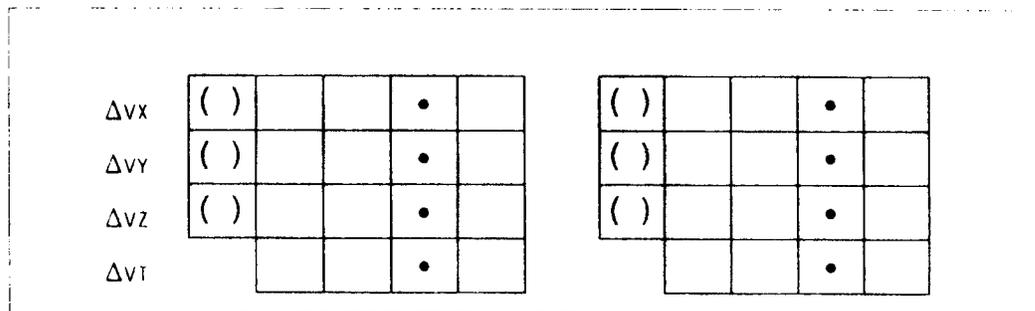


Figure 3-35.- Ti delay pad.

3.6.1.4 MC PADS

The post-Ti midcourse burns are usually small and are done axis-by-axis. Since there is no ground solution to check against, a "3-sigma variation" value is computed preflight for use as a confidence check (fig. 3-36).

The 3-sigma limits on the MC1 thru MC4 burns are for information only. They are the maximum expected value of the targeting solutions. The values are mission and burn dependent. If the limits are exceeded, the burn should still be executed, if REL NAV and the sensors being used look good.

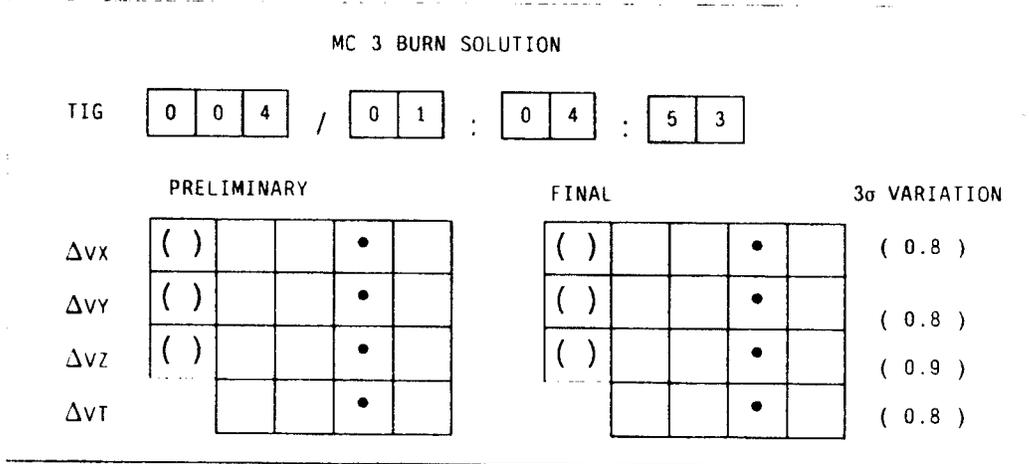


Figure 3-36.- Typical MC PAD.

3.6.2 ORBIT MNVR EXEC (MM 202)

This is the OPS display in GNC MM 202. It provides the crew with a means for inputting and executing MNVR's, evaluating their effects on the trajectory, and adjusting parameters as necessary (fig. 3-37). It can be used during long-range stationkeeping and separation as well as RNDZ.

In general, this display provides the crew interface for monitoring and control of the functions contained in MM 202. These include the controls to maneuver the Orbiter to a burn attitude, and to monitor, guide, and control the vehicle while executing a translational MNVR, or while executing the burns used in the RNDZ mission phases. The same display is used during ascent, orbit, and entry, with the difference being the title (ASCENT/ORBIT/DEORBIT MNVR EXEC/COAST). Thus, there are some items on this display that are not used in OPS 2 (e.g., PEG 4 TGT's, Items 14-18; REI-range to entry interface status, Items 35-39).

RNDZ MNVR's will be trimmed to VGO less than 0.2 ft/s in each axis. Normally, on-orbit MNVR's are not considered delta-velocity critical for flight safety or mission success, and therefore, no strict trim requirements are set. However, RNDZ MNVR's are typically considered critical for mission success and should be trimmed more accurately. Based on flight experience, 0.2 ft/s in each axis is the smallest residual consistently achievable by crew input. This accuracy is required during RNDZ operations to keep deviations from the planned profile to a minimum.

202 / /	ORBIT MNVR EXEC	XX X DDD/HH:MM:SS
OMS BOTH 1X		DDD/HH:MM:SS
L 2XS	BURN ATT	XXXX
R 3XS	24 R XXX	AVTOT XXXX.X
RCS SEL 4X	25 P XXX	TGO XX:XX
5 TV ROLL XXX	26 Y XXX	VGO X +XXXX.XX
TRIM LOAD	MNVR 27X	Y +XXX.XX
6 P ±X.X	REI XXXX	Z +XXX.XX
7 LY ±X.X	TXX XX:XX	
8 RY ±X.X	GMBL	HA HP
9 WT XXXXXX	L R	TGT XXX +XXX
10 TIC	P ±X.XS ±X.XS	CUR XXX ±XXX
XXX/XX:XX:XX.X	Y ±X.XS ±X.XS	
TGT PEG 4		
14 C1 XXXXX	PRI 28X 29X	35 ABORT TGT XX
15 C2 ±X.XXXX	SEC 30X 31X	
16 HT XXX.XXX	OFF 32X 33X	FWD RCS
17 0T XXX.XXX	GMBL CK 34X	ARM 36X
18 PRPLT ±XXXXX	XXXXXXX	DUMP 37X
TGT PEG 7		OFF 38X
19 ΔVX ±XXXX.X		SURF DRIVE
20 ΔVY ±XXX.X		ON 39X
21 ΔVZ ±XXX.X		OFF 40X
XXXX 22/TIMER 23		(XX)

Figure 3-37.- The ORBIT MNVR EXEC (MM 202) display.

Note that ORB MNVR EXEC would be used only to execute targeted translation MNVR's (via OMS or RCS). For other translation MNVR's, such as manual stationkeeping or V-BAR approach, the thrust monitor capability on REL NAV may be used to monitor manual translation command inputs from the THC, executed by RCS jets.

From flight experience, crews have suggested adding some features to OPS 202. These include the capability to perform RCS burns under GPC control and the display of time-to-go in current attitude maneuver (which is displayed in OPS 201). There are no current plans to implement these suggestions.

The RNDZ related functions of the display are described in this section. This is not a complete description of the functioning of the SPEC. For a detailed explanation of the entire display, see the DPS Dictionary or the GNC Display FSSR.

3.6.2.1 OMS BOTH/L/R, RCS SEL (Items 1-4)

These mutually exclusive items allow the user to select whether both OMS engines, or just the left or right one, or the RCS jets will be used in the upcoming MNVR. If an OMS failure is declared by fault detection, identification and reconfiguration (FDIR), a down arrow will appear in the status column next to item 2 or 3 (L or R OMS engine). The down arrow and FDI are reset if item 1 (BOTH) is subsequently selected. If item 4 is selected

(RCS SEL), the burn attitude and burn duration time computations for the targeted MNVR will be made, assuming that 2 +X RCS thrusters will be used to produce a +X acceleration. A required burn attitude will be computed to align the Orbiter +X effective thrust vector with the required thrust vector with the specified TV roll. These data will appear in Items 24-26.

3.6.2.2 Thrust Vector Roll (Item 5)

This item allows the crew to select the Orbiter orientation, in terms of roll, about the thrust vector during an OMS burn. Roll angles from 0° to 359° can be input, with 0° being heads up. It is initialized the first time to an I-loaded value (180° or heads down so the horizon is visible), and retains that value until user intervention. From then on, it comes up with the previously used value which can be changed by the user. TVR is valid only for a +X attitude burn (either +X RCS or OMS). The value of the TVR is determined by the right hand rule about the thrust vector, zero heads-up in LVLH.

3.6.2.3 Time of Ignition (Items 10-13)

These items represent the TIG in MET (DAYS/HR:MIN:SEC). A check is made by the software to ensure that a time entered in this item is realistic (within 5 minutes in the past, or 12 hours in the future). If it is not a realistic time, an illegal entry message will be generated.

3.6.2.4 PEG 7 (Items 19-21)

These items are used to input the three external ΔV 's (ft/s) in the local vertical system at ignition. When COMPUTE is performed in ORB TGT SPEC, the results are automatically transferred here (ITEM 22 must then be executed to LOAD).

Note: The burn ΔV 's may be different between the ORBIT MNVR EXEC display and the ORBIT TGT display for Lambert maneuvers. There are three reasons for this possible difference: Both displays use the current SV when computing the burn solution, but because they are used at different times some ΔV discrepancy results. If it is a Lambert targeted burn, Lambert will run through one iteration cycle when the targets are loaded on ORBIT MNVR EXEC, updating the previously computed targets for any sensed accelerations or NAV marks taken. Beginning at TIG-15 seconds, the ORBIT MNVR EXEC display starts receiving continuous updates from Lambert guidance, as compared to the ORBIT TGT display that computes the burn targets only once.

3.6.2.5 LOAD (Item 22)

The word LOAD will flash any time the display is called up in OPS 2. Once the LOAD item is executed, the word LOAD will cease flashing and the engine

selection, trim, vehicle weight, and TGT data items will be sent to guidance. Also, certain display parameters will be computed, including burn attitude, total ΔV , targeted apogee/perigee, burn time, and required ΔV in body components. The CRT timer will stop and reset to zero.

Later, if the engine selection, trim, vehicle weight, or TGT data items are altered by crew input or by ground uplink prior to burn enable or after burn completion, the word LOAD will flash, and it will be necessary to retarget the MNVR to keep Lambert guidance. Such an entry will terminate all burn guidance computations and the load-dependent parameters will blank. Any change of these targeting or setup parameters while the burn is enabled, or prior to burn completion, will be treated as an illegal entry.

3.6.2.6 TIMER (Item 23)

The GNC CRT timer may be started to count down to TIG via this item. It may already have been counting since ORB TGTING targeted the burn, but moding to 202 or execution of LOAD stopped it.

3.6.2.7 Guidance Downmoding

The active guidance mode (Lambert or external ΔV) is displayed at the bottom of the middle column. Any changes to entries on the left-hand side of MNVR EXEC will cause an automatic downmoding from Lambert to external ΔV guidance mode. To return to Lambert guidance mode, the crew must call up ORB TGT, load and recompute targets, resume MNVR EXEC, and load results. Inadvertent guidance downmoding can cause trouble with procedures which are not executed in a crisp, careful fashion. Deliberate downmoding can be achieved by intentionally changing an entry on SPEC 34 or MM 202; there are currently no known reasons for doing this.

3.6.2.8 Burn Attitude (BURN ATT, Items 24-26)

The burn attitude at ignition in degrees, with respect to the FWD ADI inertial reference frame, will appear by these items after crew execution of the load ITEM (Recall that the roll orientation about the thrust vector was specified in Item 5.) The BURN ATT items may not be used for data entry in OPS 2. Such an attempt would result in an ILLEGAL ENTRY message. The burn attitude generates ADI attitude error such that the crew can maneuver to the desired attitude. In OPS 2, this maneuver may be done automatically with the next item.

3.6.2.9 MNVR execute (Item 27)

This item enables an AUTO DAP maneuver to the desired burn attitude (given in Items 24, 25, and 26). While the maneuver is in progress, an asterisk will appear next to Item 27. If ITEM 27 has not been selected, it will be enabled automatically 10 to 15 seconds before TIG with initiation of cyclic

guidance. If it is not desired to maneuver to the burn attitude at TIG, the DAP must be placed in MAN or LVLH mode. If DAP is not in AUTO, the "*" will not appear. Note that in MM 202, the ADI error needles are referenced to BURN ATT when this item is executed.

3.6.2.10 Time to Next Apsis (TXX XX:XX)

A time is displayed (MIN:SEC) which is the time to next apsis. An alphanumeric title next to the time will read TTA if apogee is the next apsis, TTP if perigee is the next apsis, or if apogee and perigee differ by less than 5 n. mi., the time will be blank and the title will read TTC ("C" for circularization).

3.6.2.11 Burn-related parameters

Several parameters used during a burn will be displayed in the upper right-hand corner of this display.

- EXEC: This is when OMS is selected only. At TIG -15 sec, the word EXEC will appear and will flash until a keyboard EXEC is performed, at which time the characters will disappear. Ignition is inhibited until this entry is made. If the EXEC entry is made after the specified TIG, the MNVR starts immediately following the EXEC entry. Releasing the display prior to enabling the MNVR (e.g., transitioning to MM 201, OPS 3, or OPS 8) cancels that MNVR.
- ΔV TOT: This parameter identifies the predicted total ΔV of the targeted MNVR.
- TGO: This parameter reflects the predicted burn length (MIN:SEC) before TIG occurs. After ignition, it reflects the remaining burn time.
- VGO X/Y/Z: These parameters show the velocity to go componentwise in ft/s with respect to the vehicle body axis system. These values can be used by the crewmember to manually execute the required RCS burn using the THC (see section 3.6.3).
- HA, HP TGT/CUR: These parameters reflect apogee (HA) and perigee (HP) information in nautical miles for the current orbit trajectory (CUR) and for the predicted postburn orbit (TGT).

3.6.2.12 Operational Constraints

The OI-7 Program Notes (JSC-19320) lists the following operational constraints on MM 202, "ORB MNVR EXEC." Constraints on SPEC 34 also will impact MM 202 operations, see section 3.5.9, items "e", "h", and "i."

a. Attitude maneuver to unknown attitude.

On the MNVR DISP, once an AUTO MNVR (Item 27) to a desired "BURN ATT" (Items 24 through 26) is initiated, an asterisk will appear next to Item 27 to indicate that the maneuver is in progress. Once this AUTO MNVR has been initiated, this asterisk remains next to Item 27 until:

- (1) A new TGT Item is entered on the display (Items 1 through 21 except Item 18) and causes the values for "BURN ATT" to blank, but the vehicle continues to maneuver to the old "BURN ATT" (as indicated by the asterisk next to Item 27).
- (2) If a new load Item (Item 22) is entered on display, this causes a new "BURN ATT" to be computed and displayed, but the vehicle continues maneuvering to the old "BURN ATT."

In response to this problem, the crew should do the following. If an AUTO MNVR to a desired "BURN ATT" is in progress (asterisk next to Item 27) and either of the above is performed, mode the DAP to manual and back to AUTO to avoid confusion regarding the attitude to which the vehicle is maneuvering.

b. Orbit DAP RCS burns while not at guidance attitude.

Problems arise in two cases if it is desired to execute an axis-by-axis guided RCS burn in manual mode while holding some attitude other than the guidance determined burn attitude:

- (1) Without executing the MNVR Item on the ORBIT MNVR EXEC display: a maneuver to the burn attitude will begin if the AUTO mode is selected any time between TIG-15 and cutoff. Solution is to not select AUTO during this interval.
- (2) Including execution of the MNVR Item: A maneuver to the burn attitude will begin if the AUTO mode is selected any time between execution of the MNVR Item and transition out of MM 202. Solution is to prevent the maneuver, by not selecting AUTO between execution of the MNVR Item and transition out of MM 202. To interrupt the maneuver, select manual, and then AUTO (does not work during burn).

c. OPS Transition with target track active.

When an OPS mode recall (with GPC TGT set change) or OPS 2 to 8 transition is executed with RNDZ NAV enabled, RNDZ NAV will be disabled afterwards and will not be propagating the TGT SV. If the UNIV PTG TGT track option (Item 19 on the UP display) was active at the time of the OPS mode recall or OPS transition, UNIV PTG will continue to track the last computed TGT state. This may cause undesirable RCS activity. After an OPS mode recall, UNIV PTG will continue the last computed relative state. After an OPS 2 to 8 transition, the relative state is lost, and multiple GPC errors will result from operations on zero vectors.

This situation can be prevented by canceling the TGT TRK (Item 21 on the UNIV PTG display) before executing the OPS mode recall or transition. The jet firings can be stopped by moding the DAP to manual.

The GPC errors can be stopped by a PRO to MM 201 followed by canceling the TGT TRK.

If this situation occurs, a TGT state uplink is required to resume tracking. This is implemented in procedures discussed in section 6.1.3.1.

d. Stale SV after orbit OPS transition

On-orbit NAV does not execute and compute the Orbiter SV until between four and seven seconds after completion of an OPS mode recall with TGT set change or an OPS transition. During this period, the M50 to LVLH transformation quaternion will be stale and will cause the following anomalous behaviors:

- (1) The attitude displayed on any ADI for which the LVLH reference is selected will be incorrect until the SV is recomputed on the next NAV cycle (4 seconds). The crew should be aware of this.
- (2) If the DAP manual LVLH mode is initialized after the transition or recall, and before NAV runs, the commanded LVLH attitude will be based upon a stale SV. If NAV was inactive long enough during the transition or recall, and the Orbiter rates were high enough, a maneuver could result after NAV is reactivated. The crew should avoid the LVLH mode PBI during the transition or recall and for 7 seconds after resumption of GNC processing to preclude this RCS activity. Otherwise be aware of the problem.
- (3) If the DAP manual LVLH mode or a UNIV PTG Earth-relative or center-of-Earth track option is activated prior to the transition or recall, the DAP will operate on an attitude error based in part on stale data. This could result intransient jet firings until the SV is updated. The crew should be aware of this.

This constraint is flagged in section 3.7.3.4.

e. IMU data loss during MM 202 preburn maneuver:

If all IMU data is lost for at least 960 ms during a MM 202 preburn altitude maneuver, the DAP will downmode to manual rotation (MAN ROT) pulse. This downmode normally terminates the maneuver.

However, two problems may occur, if the DAP was not in the AUTO mode at any time between the start of the maneuver and the time the IMU data was lost, and:

- (1) If the IMU data is restored while in MM 202, the maneuver will re-activate immediately. (Note: The DAP will remain in the MAN ROT pulse mode). Sequential transitions to MM 201 and back to MM 202 in between the loss and restoration of IMU data will not affect this situation. The crew response should be as follows.

If the IMU data is restored while in MM 202, and,

- (a) It is desired to terminate the maneuver, execute a mode transition to MM 201, or cycle the DAP mode to AUTO, then MAN, then back to AUTO.
- (b) It is desired to continue the maneuver, either:
- Use the RHC to manually maneuver the vehicle (in any desired rotational submode) according to the ADI, or
 - Select the AUTO mode.
- (2) If the IMU data is restored while in MM 201, the maneuver will reactivate immediately upon re-entry into MM 202, unless an OPS transition out of OPS 2 is executed before returning to MM 202. The crew response should be that if the data is restored while in MM 201, either
- (a) Execute an OPS transition prior to the next entry into MM 202, or,
- (b) Mode the DAP to the AUTO mode prior to the next transition into MM 202. Then, once in MM 202, cycle the DAP mode to MAN and then back to AUTO.

This constraint is flagged in section 3.7.3.4.

3.6.3 AXIS-BY-AXIS BURNS

Under certain circumstances the ΔV required is performed in OPS 202 while holding an arbitrary attitude. There could be some compelling reason to maintain that attitude (e.g., viewing requirement, Sun angle, etc.), or the burn might be small enough that the RCS cost in maneuvering to +X and back exceeds the efficiency loss in burning axis by axis. In this case, the EXEC command is not needed and the entire burn is manually executed the same way a +X burn is trimmed postguided cutoff.

The axes are trimmed in the sequence of X, then Y, then Z, unless Z is negative and thus is to be trimmed first. This sequence minimizes the impacts of translational coupling (section 6.2.1).

This procedure is fully defined in section 3.8.5.1.

3.7 DPS

Proper processing and maintenance of RNDZ-related data is crucial to mission success. A variety of DPS activities can impact this processing, not always in obvious ways.

3.7.1 Configuration for Rendezvous

The GPC's are configured such that if either of the two computers fails during the RNDZ, vehicle attitude and translational control are maintained. This is especially important when the Orbiter is in close proximity to the TGT, and it is important for crew safety to be able to perform evasive MNVR's, should the need arise.

Stringing is accomplished to satisfy this requirement. Initially, strings 1 and 3 are on GPC 1, and 2 and 4 are on GPC 2 (NBAT is "1212").

3.7.2 Off-Nominal DPS Configurations

During actual rendezvous missions, a three-GPC redundant set has occasionally been established for redundancy reasons.

3.7.3 OPS Transition Effects

Performing OPS mode recalls or OPS transitions during the RNDZ phase can have significant impact on procedures. Where possible, such transitions should be delayed to the PROX OPS phase or later.

OPS mode recalls that are associated with the addition/deletion of a GPC to/from the GNC redundant set result in a number of undesirable secondary effects because of the momentary passage through OPS zero, particularly when rendezvous NAV is enabled. Among these are the disabling of RNDZ NAV, loss of the propagated NAV state, covariance matrix reinitialization, possible bad NAV measurements being incorporated into the filtered NAV state, an undesired attitude maneuver accompanied by the "pegging" of the ADI error needles, GPC errors, and increased propellant usage.

In addition, DPS OPS transitions are performed in accordance with several malfunction procedures. As a minimum, RNDZ NAV is disabled. In some cases, base time, target state vector, covariance matrix, and universal pointing can also be lost. GPC errors may also occur.

3.7.3.1 RNDZ NAV Termination

RNDZ NAV is terminated any time OPS 2 is left (see section 3.6.2.12, item "c"). This will happen when an OPS transition (OPS 2-X-2) is performed (for X = 8 or X = 3) or when a GPC is add/deleted to/from the set by performing an OPS/mode recall. RNDZ NAV is not terminated due to restringing.

In the ORB PKT C/L procedure for "PASS GNC GPC (1st FAIL)", there are steps which call out:

IF RNDZ NAV Enabled:

Perform RNDZ NAV SAFING

and after the OPS manipulations

IF RNDZ NAV REQ'D:

Perform RNDZ NAV Recovery

The two procedures, for safing and for recovery, are found in figures 3-38 and 3-39. Their specific uses and rationales are described below in three subsections.

- a. The OPS 2-8-2 transition is necessary when starting an APU. The procedures are located in the orbit operations checklist, "G2 to G8 Transition" and "G8 to G2 Transition."

RNDZ NAV will be terminated on departure from OPS 2 since it is not supported in OPS 8. On return to OPS 2 the NAV software level, called "OPS overlay" (highest or last level), is read from the MMU. This means all NAV software at the "OPS overlay" level is in an I-loaded state. Target SV, covariance matrix, and base time are all lost. RNDZ NAV and KU ANT functions are terminated because they are not supported in OPS 8.

(Text continues on page 3-102.)

```

If OPS MODE recall (ADD/DELETE GPC
TO/FROM Redundant Set)

DAP: FREE DRIFT
GNC UNIV PTG
CNCL - ITEM 21 EXEC (*)
If OPS TRANSITION (G2 to G8/G3)
Before OPS transition :
.....If MNVR for APU leak reqd.....
. -Y FOR STRK (+Y for RR) .
. GNC UNIV PTG .
. TGT ID +1 .
. BODY VECT +5 .
. P +0 .
. Y +280.6 (+90) .
. OM +90 (+180) .
. TRK - ITEM 19 EXEC (*) .
. DAP: B/AUTO/NORM, .
. When in att, DAP: A/AUTO/VERN .
. NOTE: Do not take RR Angle data .
. while in +Y attitude .
.....

CRT GNC 34 ORBIT TGT
Record Base Time __/__:__:__

```

Figure 3-38.- RNDZ NAV safing.

After returning to OPS 2, the MCC uplinks a new TGT SV (RNDZ NAV cannot be enabled until this is done) and COV MATRIX. The crew enables RNDZ NAV and KU ANT and returns to TGT TRK, then selects appropriate angle sensor (RR, STRK, or COAS, initiated as STRK) and incorporates sensor data into NAV when appropriate.

If OPS MODE recall (add/delete GPC to/from redundant set)

CRT

GNC 33 REL NAV

Inhibit RNG - ITEM 18 EXEC
 RDOT - ITEM 21 EXEC
 Angles - ITEM 24 EXEC

[Note: * will not change until RNDZ NAV enabled]

RNDZ NAV ENA - ITEM 1 EXEC (*)
 ✓KU ANT ENA - ITEM 2 as reqd
 GNC I/O reset - EXEC

CRT

GNC UNIV PTG

✓TGT ID, BODY VECT, P, Y, OM
 TRK - ITEM 19 EXEC (*)
 DAP: A/AUTO/VERN

CRT

GNC 33 REL NAV

Auto RNG - ITEM 17 as reqd
 RDOT - ITEM 20 as reqd
 Angles - ITEM 23 as reqd

When SV UPDATE POS < 1.0 (0.3 if RR)
 and MARK ACCEPT > 9,
 SV SEL - ITEM 4 EXEC (FLTR)

(MORE)

Figure 3-39.- RNDZ NAV recovery.

	IF OPS TRANSITION (G8/G3 to G2)
	After returning to OPS 2:
	After ground uplink of TGT SV, COV MATRIX,
CRT	GNC 33 REL NAV
	RNDZ NAV ENA - ITEM 1 EXEC (*)
	✓KU ANT ENA - ITEM 2 as reqd
	GNC I/O reset - EXEC
CRT	GNC UNIV PTG
	✓TGT ID, BODY VECT, P, Y, OM
	TRK - ITEM 19 EXEC (*)
	DAP: A/AUTO/VERN
CRT	GNC 33 REL NAV
	S TRK (RR, COAS) - ITEM 12 (13, 14) EXEC (*)
	Auto RNG - ITEM 17 as reqd
	RDOT - ITEM 20 as reqd
	Angles - ITEM 23 as reqd
	When SV UPDATE POS < 1.0 (0.3 if RR) and MARK ACCEPT > 9,
	SV SEL - ITEM 4 EXEC (FLTR)
CRT	GNC 34 ORBIT TGT
	TGT NO - ITEM 1 +1 EXEC
	Set BASE TIME, ITEM 21 to value as recorded above
	LOAD - ITEM 26 EXEC
	(MORE)

Figure 3-39.- Continued.

```

.....If MNVR for APU leak was reqd.....
.
. After APU burn complete, mnvr to
. reqd TGT TRK attitude:
.
. -Z TGT TRK (-Y STRK)
.
. GNC UNIV PTG
.
. TGT ID +1
. BODY VECT +3 (+5)
. P +90 (+0)
. Y +0 (+280.6)
. OM +0 (+90)
. TRK - ITEM 19 EXEC (*)
. DAP: B/AUTO/NORM,
. When in att, DAP: A/AUTO/VERN
.
. NOTE: Do not take RR angle data
. while in -Z TGT TRK att
. (if appropriate)
.
.....

```

Figure 3-39.- Concluded.

If an actual maneuver to APU burn attitude was required, the crew performs the steps shown in figure 3-39.

- b. The OPS 2-3-2 transition is used any time it is necessary to use the master X-feed switch (not available in OPS 2). It is also possibly used in RCS/OMS leak isolation. Another use is if both G2 GPC's fail.

The procedures are located in malfunction procedures: G2/G8 TO G3 TRANS (5-119); G3 TO G2/G8 TRANS (5-119); TWO GPC FAIL (5-62).

The effect is similar to an OPS 2-8-2 transition, and the fix is the same as OPS 2-8-2 transition.

- c. Adding a GPC to the redundant set (OPS/Mode recall) is an OPS transition, even though it is not readily obvious. Any time a GPC is brought into the set an OPS MODE RECALL is performed.

The procedure is located in the Orbit Pocket Checklist (PASS GNC GPC (1st FAIL)) and in the malfunction procedures (PASS GNC GPC (1st FAIL); SINGLE GPC FAIL (5-60); DPS RECONFIG FOR LOSS OF AV BAY COOLING (5-83); GNC REASSIGNMENT (5-104)).

The ITEM 21 (CNCL) is performed to prevent annunciation of GPC errors due to divide-by-zero, and pegging of ADI needles.

The effect of an OPS MODE RECALL is slightly different from an OPS TRANSITION. If a GPC is brought into the set, the crew will change the GPC TGT set in the NBAT and then perform an OPS/Mode recall (OPS XXX

PRO). This momentarily takes all GPC's in the set to OPS 0 to synchronize them and then returns them to the appropriate OPS (in this case OPS 2). RNDZ NAV is terminated upon leaving OPS 2 (RNDZ NAV is not supported in OPS-0). Upon return to OPS 2, the "OPS overlay" software is read from the G2 GPC, not the MMU. This means one comes back into OPS 2 in basically the same configuration in which one is left, except RNDZ NAV is not automatically reenabled. The target SV is not being propagated; when RNDZ NAV is reenabled, the TGT SV is propagated forward to the current time. Also, when RNDZ NAV is manually re-enabled, a FLTR to PROP and COVAR REINIT are automatically performed and the PROP SV is automatically selected.

3.7.3.2 ORB TGT'ing

Computation is terminated and must be manually restarted.

3.7.3.3 Attitude Control

Failure to go to free drift on transition to OPS 8 can have damaging effects. Since the TGT SV is frozen (it tracks where the TGT was when OPS 2 was left), the DAP can get confused if it hits a DB; multiple jet firings may result. There would also be a large attitude maneuver when OPS 2 is resumed.

3.7.3.4 Star Tracker

OPS transition (8 to 2 or 2/0/2 for set change) will cause STRK processing to go to TERM IDLE. The STRK acquisition procedure must be performed after returning to OPS 2.

3.7.3.5 Other Effects

The covariance matrix and NAV sensor mark counters are reset. Also, see section 3.6.2.12 for MM202 OPS constraints involving DPS transitions (especially items "d" and "e").

3.8 OMS/RCS ISSUES

3.8.1 RCS Cross-Coupling

Due to the awkwardly unsymmetric alignments of the physical arrangement of the RCS jets (fig. 3-41), commanded translation/rotation maneuvers in one axis tend to induce motion in other axes as well. This effect is called "cross-coupling." It can have significant impact on manual flying during RNDZ terminal phase and PROX OPS.

A complete description of Orbiter PRCS-induced acceleration is given in figure 3-42. To be useful for understanding the magnitude of the problem, however, a better representation would show the relative accelerations normalized (that is, the desired acceleration is set to "1," and the sizes of the other accelerations proportioned accordingly). Such a cross-coupling ratio table is given in figure 3-43 (normal and low-Z modes) and figure 3-44 (nose only and tail only modes), and should be taken only as an indicator of relative cross-coupling effects.

In order to make quantitative comparisons of rotation and translation cross-couplings, a proportionality constant had to be derived to allow unitless ratios to be computed. The scheme was developed to set this proportionality constant to the value that gave equal ratios of each type of motion cross-coupling to the primary commanded motion; that is, once properly adjusted, the ratio of commanded rotation rates to the undesired induced translation rates would be the same as the ratio of commanded translation rates to the undesired induced rotation rates. A satisfactory value was found to be approximately 3 times the translation rates in feet; in practice, this creates equivalence (1 deg = 3 feet) at a range of about 150 to 200 feet, where in fact much PROX OPS maneuvering occurs. Because this is an arbitrary scheme, the values in the proportional tables must be used properly and not misinterpreted. However, the tables do provide qualitative cross-coupling ratios which are entirely consistent with, and often explain some superficially puzzling dynamics aspects of, both simulations and flight experience.

In examining the translational impacts of specific RCS firings, one further step is necessary. Where any translation is directly induced, that is immediately added to the totals; where a rotation is induced, that rotation is nulled with a "perfect" opposite rotation command and the translational impacts of that theoretical maneuver are added to the totals. This computation algorithm continues until all rotational impacts have been nulled. This technique will provide useful results, but in the real world there may actually be overcorrection for the rotational cross-couplings, with consequently different total translational impact.

The "attitude hold" section for rotation maneuvers is computed by performing a unit rotation maneuver and then immediately nulling it with an opposite sense rotation maneuver, restoring rates to zero in that axis. The induced rates in other axes are then computed and nulled, and the resultant translational cross-couplings are summed.

Not surprisingly, the different DAP modes give markedly different amounts of translational cross-coupling from the same sized rotation maneuvers. These are shown in figure 3-40, where the roll-pitch-yaw coupling into Orbiter body X and Z axes are displayed (there is no significant coupling into the Y axis). DAP NORM is the lowest (the "cleanest") on this scale, and the TAIL-ONLY and NOSE-ONLY options are also both quite "clean." At the opposite extreme, vernier jets are the "dirtiest" in terms of translational cross-coupling from rotation maneuvers, especially in that such cross-coupling occurs exclusively in the -Z axis. DAP LOW Z is almost as bad, and since

some DAP configurations call for larger rotation rates, the total cross-coupling magnitude will be greater.

DAP mode:	In X axis:	In Z axis:	Avg:
NORM (R,P,Y)	+0.26,+0.00,+0.26	+0.26,+0.02,+0.00	0.1
LOW Z (R,P,Y)	+0.50,+0.50,+0.00	-2.00,-2.00,-0.00	0.8
Tail Only (R,P,Y)	* ,+0.50,+0.00	* ,+0.00,+0.00	0.2
Nose Only (R,P,Y)	* ,+0.00,+0.00	* ,+0.00,+0.00	0.1
VERN (R,P,Y)	+0.00,+0.00,+0.00	-1.50,-2.00,-2.00	0.9

Figure 3-40.- DAP vs translational cross-coupling (unitless ratio value) * = same as NORM.

3.8.1.1 Translation Effects

The analysis generates some very useful insights into cross-coupling effects, and conforms to experience in flight and in simulators. The following effects should be specifically noted (assume Orbiter is on TGT V-BAR, tail-to-earth and bay-to-TGT):

NORM ROLL: This is clearly the "dirtiest" maneuver, with measurable cross-coupling in every other degree of freedom except yaw. This is far worse in low Z.

NORM +/-X: This induces significant +Z (braking) translations, and thus the closing rate needs to be put back in (see section 3.2.4.2 and 4.4.2). This is also true in low-Z +X, but it is not true in low-Z -X.

NORM -Z (closing): These pulses also induce significant +X ("up") translation. Same in low-Z.

LOW-Z +Z (braking): In free drift, this induces major negative pitch; in attitude hold, the translation pulse loses half its force in the subsequent counteraction of attitude deviation.

Low-Z +/-Y: When in attitude hold, these firings induce major -Z (closing) rates, more than half the size of the commanded Y-axis translation.

ROLL/PITCH deadbanding: In NORM, this generally induces a small +Z (away from TGT) force; in low-Z, however, this induces a major -Z (closing) force. In low-Z, minus pitch also produces a significant +X translation.

TAIL-ONLY: This off-nominal control mode has several unique cross-coupling characteristics. Pitch induces a powerful Z translation, and

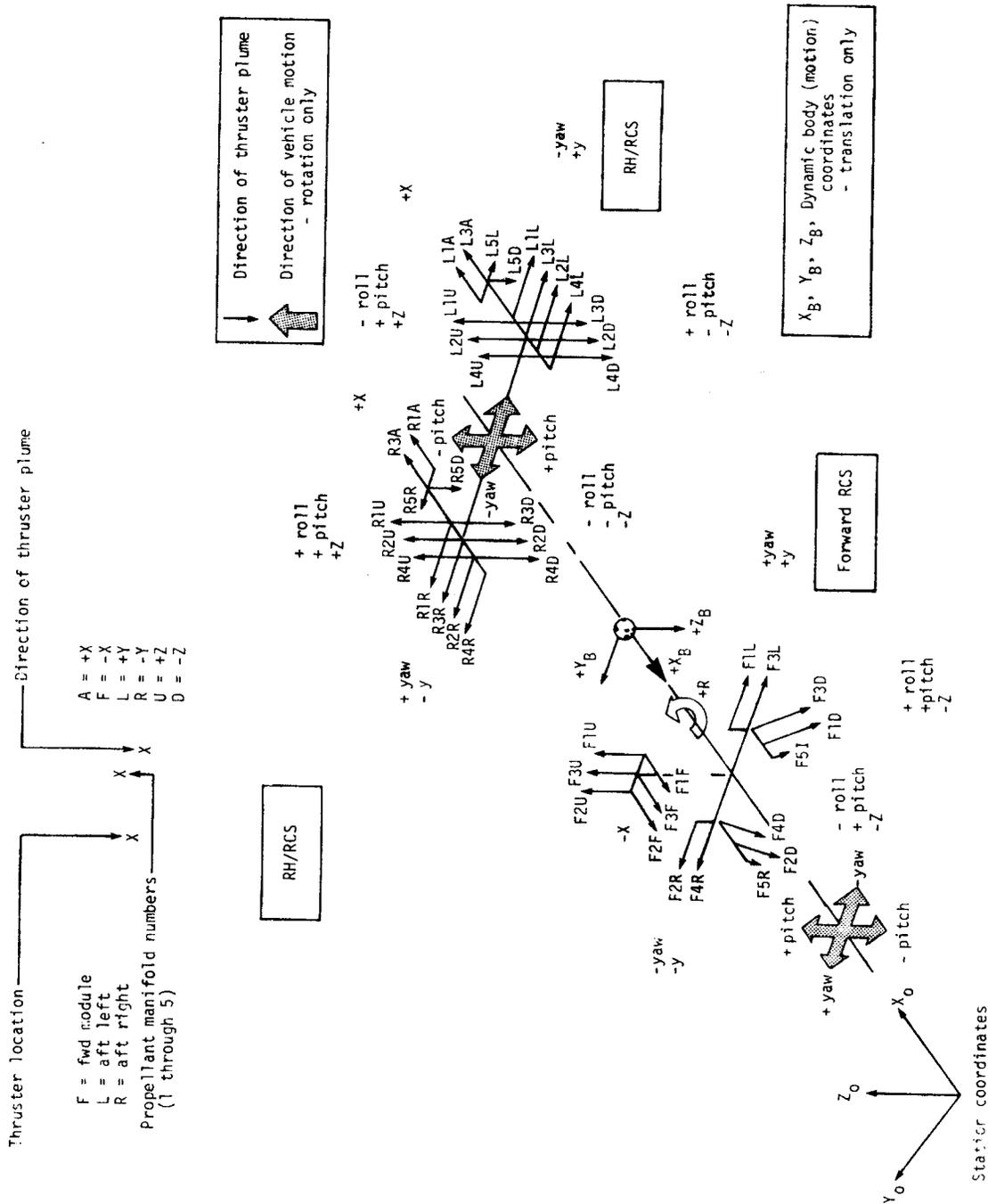


Figure 3-41.- RCS jets.

Orbiter's Acceleration Rates

Orbiter data for STS-7 PLBD closed (End of Mission)
 $I_{xx}, I_{yy}, I_{zz} (\text{S.FT.}^2)$ 924,014.1 , 6,783,809.4 , 7,084,050.2
 $I_{xy}, I_{xz}, I_{yz} (\text{S.FT.}^2)$ 3,658.3 , 195,815.6 , -710.1
 $X_{cg}, Y_{cg}, Z_{cg} (\text{in.})$ 1,105.1 , -0.4 , 375.2
 Orbiter Weight (lbf) 214,048.4

DAP Config	Jet Group	Jets Fired	rate in X_o (FT/S ²)	rate in Y_o (FT/S ²)	rate in Z_o (FT/S ²)	roll rate (Deg/S ²)	pitch rate (Deg/S ²)	yaw rate (Deg/S ²)
NORM	+roll	R1U, L3D	0.03170	0.03642	0.04458	0.87613	0.08571	-0.03082
NORM	-roll	L1U, R3D	0.03170	-0.03642	0.04458	-0.87521	0.08478	0.03054
NORM	+pitch	F4D, F3D, L1U, R1U	-0.00743	0.00000	0.07004	0.00585	1.21710	0.00005
NORM	-pitch	F3U, L3D, R3D	0.05858	0.00000	-0.04190	-0.00473	-0.82885	-0.00013
NORM	+yaw	F3L, R3R	-0.00268	0.00023	0.00080	-0.27285	-0.00118	0.68088
NORM	-yaw	F4R, L1L	-0.00268	-0.00023	0.00080	0.27093	-0.00094	-0.68853
NORM	+X	R3A, L3A	0.25778	0.00000	0.04548	0.00044	-0.02227	-0.00046
NORM	-X	F2F, F1F	-0.26458	0.00000	0.03607	0.00017	-0.11276	0.00049
NORM	+Y	F3L, L1L	-0.00268	0.26162	0.00080	0.31098	-0.00101	0.17908
NORM	-Y	F4R, R3R	-0.00268	-0.26162	0.00080	-0.31268	-0.00109	-0.18674
NORM	+Z	F3U, L1U, R1U,	-0.00477	0.00000	0.39382	0.00572	0.07387	0.00018
NORM	-Z	F4D, F3D, L3D, L2D, R3D, R2D	0.11926	0.00000	-0.53898	-0.00950	-0.03658	-0.00043
Low Z	+Z	F1F, F2F, R3A, L3A	-0.00880	0.00000	0.08154	0.00081	-0.13504	0.00004
Low Z	+roll	L3D	0.03168	0.04790	-0.08665	-0.38733	-0.18287	-0.06782
Low Z	-roll	R3D	0.03168	-0.04790	-0.08665	-0.39209	-0.18328	0.06764
Low Z	+pitch	F4D, F3D	-0.00748	0.00000	-0.19238	-0.00004	0.88045	-0.00008
Low Z	-pitch	L3D, R3D	0.06338	0.00000	-0.17330	-0.00478	-0.36818	-0.00019
Tail only	+pitch	L1U, R1U	0.00003	0.00000	0.26242	0.00568	0.53665	0.00010
Tail only	-pitch	L3D, R3D	0.06338	0.00000	-0.17330	-0.00478	-0.36818	-0.00019
Tail only	+yaw	R3R	0.00050	-0.13070	0.00072	-0.29287	-0.00063	0.24708
Tail only	-yaw	L1L	0.00050	0.13070	0.00072	0.29095	-0.00047	-0.25473
Nose only	+pitch	F4D, F3D	-0.00748	0.00000	-0.19238	-0.00004	0.88045	-0.00008
Nose only	-pitch	F3U	-0.00480	0.00000	0.13140	0.00004	-0.48278	0.00008
Nose only	+yaw	F3L	-0.00318	0.13092	0.00008	0.02002	-0.00053	0.43381
Nose only	-yaw	F4R	-0.00318	-0.13092	0.00008	-0.02002	-0.00048	-0.43380

Figure 3-42.- RCS axis cross-coupling values.

...The Orbiter also gets these:

For cmded accels...		In free drift						Under attitude hold				
		X	Y	Z	R	P	Y	X	Y	Z		
NORM-Z	ROLL	+	+1/9	+1/8	+1/7	⊗	+1/10	0	0.26	0	0.26	
		-	+1/9	-1/8	+1/7	⊗	+1/10	0				
	PITCH	+	0	0	+1/6	0	⊗	0	0.20	0	0.02	
		-	+1/5	0	-1/7	0	⊗	0				
	YAW	+	0	0	0	-1/2	0	⊗	0	0	0	
		-	0	0	0	+1/2	0	⊗				
	+X	⊗	0	+1/6	0	0	0	+1.00	0	0.17		
	-X	⊗	0	+1/7	0	-1/7	0	-1.00	0	0.17		
	+Y	0	⊗	0	+1/3	0	+1/4	0.04	+0.95	-0.07		
	-Y	0	⊗	0	-1/3	0	-1/4	0.04	-0.95	-0.07		
	+Z	0	0	⊗	0	0	0	0	0	+1.00		
	-Z	+1/5	0	⊗	0	0	0	+0.20	0	-1.00		
	LOW-Z	ROLL	+	+1/4	+1/3	-1/2	⊗	-1/2	-1/6	0.5	0	-2
			-	+1/4	-1/3	-1/2	⊗	-1/2	+1/6			
PITCH		+	0	0	-1	0	⊗	0	0.5	0	-2	
		-	+1/2	0	-1	0	⊗	0				
YAW		±	same as NORM-Z						0 to .5	0	0 to -1	
		+X	same as NORM-Z						+1.00	0	0.17	
		-X	same as NORM-Z						-1.00	0	0	
		±Y	same as NORM-Z						0.12	±0.83	-0.50	
		+Z	-1/12	0	⊗	0	-1/2	0	0.08	0	0.50	
		-Z	same as NORM-Z						+0.20	0	-1.00	

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Figure 3-43.- PRCS cross-coupling ratios.

		Free drift						Attitude hold			
		X	Y	Z	R	P	Y	X	Y	Z	
TAIL-ONLY	PITCH	+	0	0	+1	0	⊗	0	.5	0	0
		-	+1/2	0	-1	0	⊗	0		0	
	YAW	+	0	-2	0	-1	0	⊗	0	0	0
		-	0	2	0	+1	0	⊗	0	0	0
NOSE-ONLY	PITCH	+	0	0	-1	0	⊗	0	0	0	0
		-	0	0	+1	0	⊗	0	0	0	
	YAW	+	0	+1	0	0	0	⊗	0	0	0
		-	0	-1	0	0	0	⊗	0	0	

roll = same as nominal

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Figure 3-44.- PRCS off-nominal cross-coupling ratios.

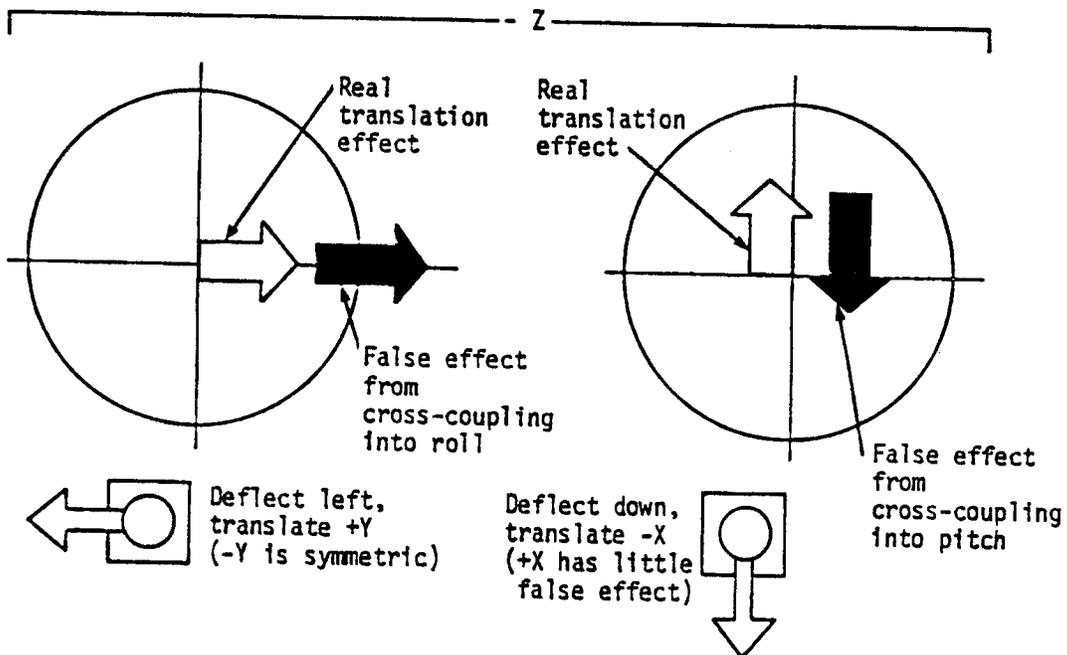


Figure 3-45.- TGT LOS cross coupling aft THC, -Z sense 200 foot range.

Motion shown is prior to hitting DB.

pitch also induces significant +X translation. Yaw induces an extremely powerful Y translation and noticeable X and Z translations as well. All other control modes are identical to normal control.

NOSE-ONLY: This off-nominal control mode also has its own peculiar cross-coupling characteristics. In pitch, translational effects are the mirror-image of tail-only control (but with no X effects); in yaw they are also the opposite sense to tail-only, but much reduced.

3.8.1.2 LOS Cross-Coupling Effects

When observing a target out the overhead window, the crewmember may command RCS translation maneuvers perpendicular to the LOS in order to control Orbiter/TGT relative position (in a "fly to" mode). Because of induced rotations, the initial LOS motion of the TGT may be momentarily misleading (see fig. 3-45). The following examples are based on a target at a range of 200 feet:

NORM/LOW-Z "+Y" translation: Commanding a +Y pulse (to the left, when facing aft) results in angular rates due both to translation and also momentarily to rotation (until a DB is hit). Both rates are to the right, but the momentary rotation-induced LOS motion is FOUR TIMES the size of the translation-induced LOS rate. The translation-induced rate only gets as large as the rotation-induced rate at a range of 50 feet.

NORM/LOW-Z "-Y" translation: Symmetric opposite to +Y.

NORM/LOW-Z "-X" translation: Commanding a -X pulse results in a translation-induced LOS motion upwards and a rotation-induced motion downwards (the Orbiter performs a minus pitch). At 200 feet, the translation-induced rate is slightly smaller than the rotation-induced rate, so the TGT will actually appear to move downwards, opposite to the desired (and commanded) sense, at least until a DB is hit. At 100 feet, the motion will clearly be in the proper direction, but only a fraction of the actual true LOS rate due to rotation-induced LOS motion, until deadbanding occurs.

NORM/LOW-Z "+X" translation: Rotational rates are very small.

These effects accentuate the need for the crewmember to be patient after performing translation pulses, to see the LOS motion after deadbanding, and not be misled by the initial LOS rates (which may contain deceptive rotation-induced components).

3.8.1.3 VRCS Effects

Vernier RCS jets induce their own cross-coupling, and although the jets are smaller than primary jets, their geometry is even more awkward. The accelerations are shown in figure 3-46 (both free drift and attitude hold,

RCS/DAP RESPONSE MATRIX
 JET SELECT OPTION V, NO COMPENSATION
 (FREE DRIFT)

*****ACCELERATIONS*****
 TRANSLATIONAL (FT/SEC/SEC) ROTATIONAL (DEG/SEC/SEC)

CMD	X	Y	Z	R	P	Y
+ROL	-0.00006	0.00699	-0.00483	<u>0.02417</u>	0.00557	0.00119
-ROL	-0.00006	-0.00699	-0.00483	<u>-0.02418</u>	0.00553	-0.00119
+PCH	0.00025	0.00000	-0.00544	0.00009	<u>0.02060</u>	0.00000
-PCH	0.00012	0.00000	-0.00404	-0.00009	<u>-0.00909</u>	-0.00000
+YAW	-0.00012	-0.00108	-0.00281	-0.00311	0.01009	<u>0.01717</u>
-YAW	-0.00012	0.00108	-0.00281	0.00319	0.01010	<u>-0.01717</u>

RCS/DAP RESPONSE MATRIX
 JET SELECT OPTION V, ROT COMPENSATION
 (ATTITUDE HOLD)

*****ACCELERATIONS*****
 TRANSLATIONAL (FT/SEC/SEC) ROTATIONAL (DEG/SEC/SEC)

CMD	X	Y	Z	R	P	Y
+ROL	0.00001	0.00707	-0.00781	<u>0.02433</u>	0.00000	0.00000
-ROL	0.00001	-0.00707	-0.00780	<u>-0.02446</u>	0.00000	0.00000
+PCH	-0.00025	-0.00003	-0.00545	0.00000	<u>0.02063</u>	0.00000
-PCH	0.00012	0.00003	-0.00406	0.00000	<u>-0.00907</u>	0.00000
+YAW	0.00002	-0.00015	-0.00827	0.00000	0.00000	<u>0.01733</u>
-YAW	-0.00002	0.00019	-0.00830	0.00000	0.00000	<u>-0.01733</u>

Figure 3-46.- VRCS Cross-Coupling.

where ALL attitude cross-coupling is taken out and converted into translation cross-coupling), and a normalized ratio table is given in figure 3-47.

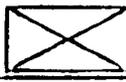
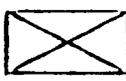
The most striking observation is that ALL vernier firings wind up inducing translational cross-couplings of roughly equivalent size in the same body axis, the -Z direction. During the rendezvous phase, over a long period of time, such translational cross-coupling could induce significant downtrack errors in Orbiter position, despite the individually minute force of each single firing. The firings do not randomly cancel out; instead, they accumulate preferentially in one Orbiter body direction.

3.8.1.4 Cross-Coupling Examples

Several examples can illustrate the role that translational cross-coupling can play in rendezvous and PROX OPS trajectories. (See figure 3-47.)

During quiescent periods of PROX OPS, even just simple pitch/yaw deadbanding in low Z mode or in verniers can quickly introduce a clear-cut -Z translation. Analysis (confirmed by SES simulations) indicates that a rule-of-thumb for this -Z translation is "35 to 40 pounds of propellant per -Z ft/s"; that is, the expenditure of 35 to 40 pounds of propellant through the RCS during attitude hold will result in a cross-coupling translation of 1 ft/s in the -Z direction. Use of propellant consumption to monitor this -Z buildup may be more reliable than watching AVG G on SPEC 33 (REL NAV) due to IMU noise accumulation and the fact that much of the cross-coupled -Z acceleration would be below the threshold of measurement by AVG G. The time period in which this -Z buildup occurs will vary depending on how stable the Orbiter attitude was when attitude hold was initiated. This -Z buildup effect is liable to be significant during close-range stationkeeping and especially during gentle separations; failure to monitor it could quickly lead to the appearance of uncomfortable closing rates. Note that in efficiency this result is not far different from a deliberate RCS axis-by-axis translation burn.

Maneuvering to attitude can induce trajectory dispersions whose severity depends on the DAP mode. Assuming an Orbiter in target track, nose to Earth, an 0.2 deg/s attitude maneuver to nose-forward heads-up for a +X burn and subsequent return to target track will induce translational cross-coupling. If the maneuver is performed in NORM, the total velocity deviation is about 0.022 ft/s, mainly in the -R-BAR (up) direction, and this can be safely disregarded since the burn itself is only trimmed to 0.200 ft/s. However, if both the attitude maneuvers are performed in VERN, the significant propellant savings are offset by a much higher velocity impact: the total deviation is about 0.213 ft/s, 10 times that with the NORM jets, and much of that (about 0.1 ft/s) is in the +V-BAR direction (25 times as much as with DAP NORM), which accumulates downtrack error. The result would be as serious as a sloppy trim of burn residuals, and this could definitely be apparent on subsequent navigation and targeting.

		Free drift					Attitude hold			
		X	Y	Z	R	P	Y	X	Y	Z
ROLL	+	0	+1	-1/2		+1/4	0	0	+1	-1.5
	-	0	-1	-1/2		+1/4	0	0	-1	
PITCH	+	0	0	-1	0		0	0	0	-2
	-	0	0	-1	0		0	0	0	
YAW	+	0	-1/5	-1/2	-1/5	+1/2		0	0	-2
	-	0	+1/5	-1/2	+1/5	+1/2		0	0	

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Figure 3-47.- VRCS cross-coupling ratios.

3.8.2 Plumes

Plumes from rocket engines are of concern due both to dynamic effects on payloads and to contamination. These concerns impact engine firing procedures, both for the Orbiter and for payloads.

3.8.2.1 RCS Plumes

The influence of RCS plume effects on PROX OPS flight techniques is discussed in section 3.2.4, Low Z Operations. The RCS plume overpressures near the Orbiter are shown in figure 3-10.

The RCS plumes (both NORM Z and low Z) at greater ranges (out to 1400 feet) are shown in figures 3-48 and 3-49.

3.8.2.2 OMS Plume

The OMS plume for a single engine burn is shown in figure 3-50, out to about half a mile. See also figure 5-26 in section 5.4.1, Nominal Separation.

3.8.2.3 PL Plume

PROX OPS restrictions on payload thrusting are illustrated in figure 3-51. The source is the memo, Safe Distance for Firing of Liquid Propellant Engines, NS2/83-L167, from LA/Manager, NSTSPO, dated June 10, 1983.

3.8.3 Failure Modes

Various types of OMS/RCS failures can impact RNDZ and PROX OPS procedures.

3.8.3.1 Jet Fail On

The concern for a failed-on PRCS jet is a momentary disturbance to Orbiter attitude. Although opposing jets would automatically try to compensate (if in proper DAP mode), the initial perturbation could be significant in terms of translational velocity and attitude (e.g., instrument pointing or docking misalignment). If the opposing jets were able to overcome the failed-on jet, an attitude oscillation would occur as the vehicle was driven back to within the attitude/rate DB's. If the opposing jets were then turned off, this would allow the failed-on jet to again drive the Orbiter out of the DB resulting in more translation. A fail-on vernier jet would produce the same scenario, but attitude/rate offsets would be smaller.

There is a single-point failure which can cause this to occur, which involves the shorting out of either of two output transistors in the reaction jet driver. However, Rockwell has reported that the mean time between failures for these transistors is five billion hours (about half a million years).

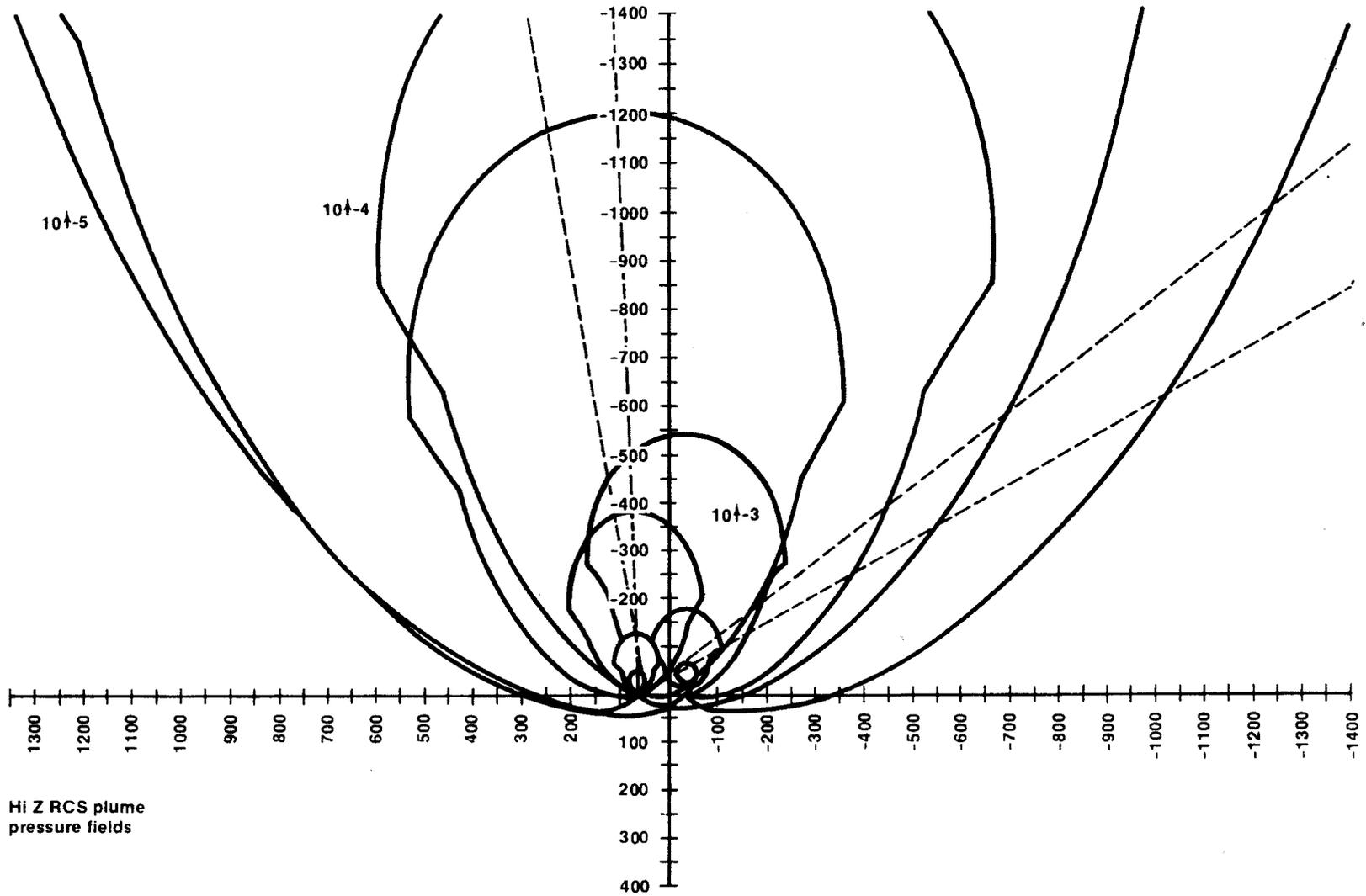


Figure 3-48.- Norm Z RCS plume pressure fields.

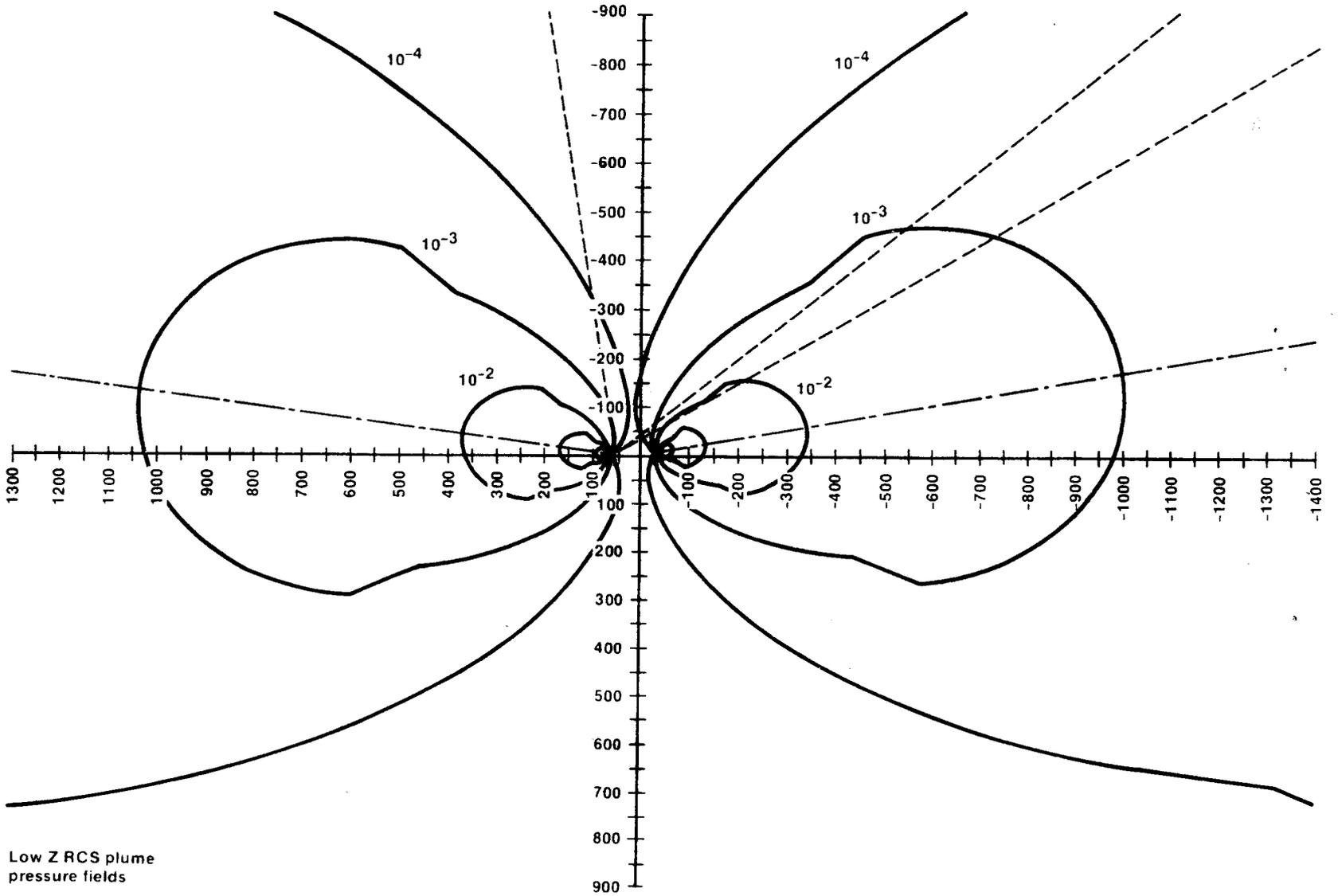


Figure 3-49.- Low Z RCS plume pressure fields.

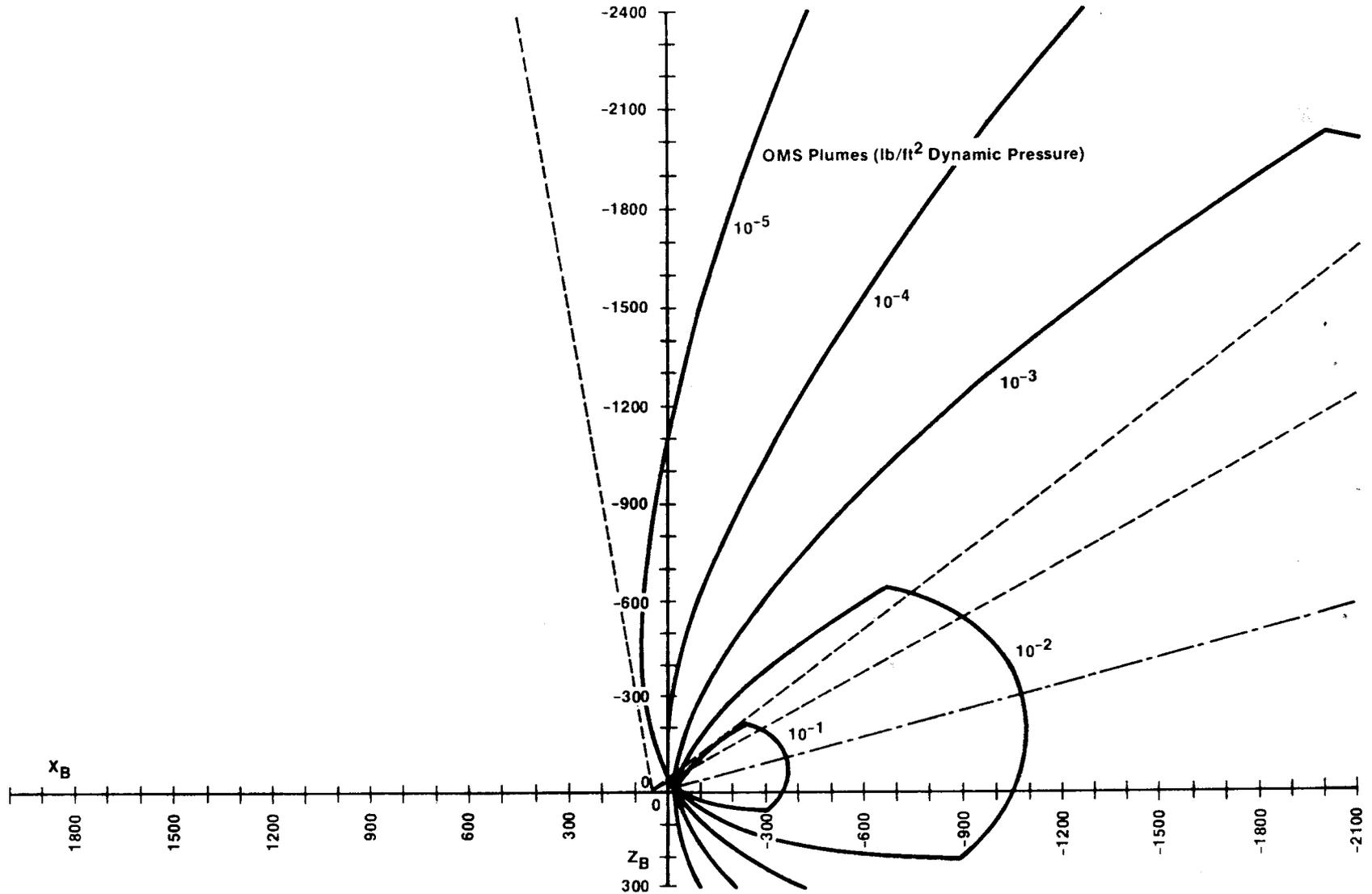
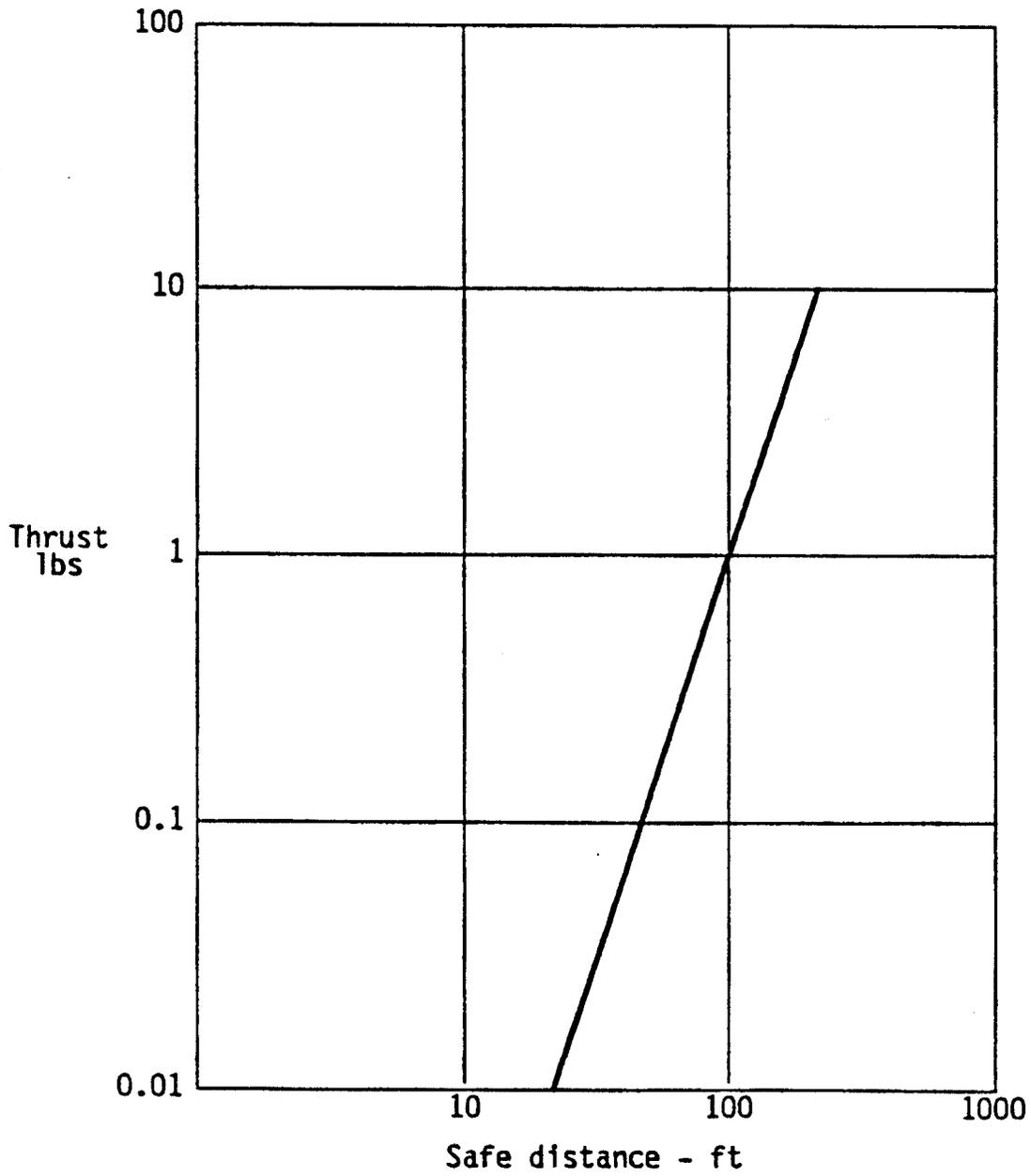


Figure 3-50.- OMS plume for single engine burn.



10589*004

Figure 3-51.- Safe distance for firing liquid propulsion engines (paragraph 3.8.2.2).

In practice, the possibility of a failed-on jet has been handled informally by crews. On STS 51-F, during precise PROX OPS phases, the pilot was stationed in the forward cockpit with the responsibility of shutting off the proper manifold should a fail-on occur.

The current belief is that such a failure is highly unlikely and therefore does not require procedures to guard against it.

3.8.3.2 OMS Overburn

Failure to perform AUTO cutoff at VGO = 0 may occur due to a GPC failure during the burn if both valves have coil open commands strung together. In response, the crew manually takes ARM PRESS SW(s) to OFF. It is probably cheapest and safest to trim out the extra-high residuals immediately rather than waiting until the next scheduled burn; this is especially true at Ti. Flight experience has been that in the first 25 STS missions there have been 5 on-orbit GPC failures, none during OMS burns. Significant analysis has not been performed.

3.8.3.3 Loss of VRCS

See section 4.4.3.

3.8.3.4 Loss of Low Z Mode

See section 4.4.4.

3.8.4 Quantities

3.8.4.1 Rendezvous OMS/RCS PRPLT PAD

This pad (fig. 3-52) is used to reconfigure the OMS/RCS system due to low prop levels, and to abort the RNDZ, if required, due to low prop levels. Usage is defined in section 4.3.4. If breakout is performed, it provides a "disable RNDZ NAV" procedure.

```

When L or R RCS QTY < _____:
  I'CONNECT: L OMS to RCS (ORB PKT, RCS)

When G23 L OMS/RCS QTY > _____:
  I'CONNECT TK SWITCH: From L to R OMS FEED
  (ORB PKT, RCS)

When G23 R OMS/RCS QTY > _____:
  I'CONNECT RETURN (ORB PKT, RCS)

-----
When L or R RCS QTY < _____:
  or when FRCS QTY < _____:

DAP: NO LOW Z

-----
When L or R RCS QTY < _____:
  or when FRCS QTY < _____:

If prior to Ti,
  Do not perform Ti

If after Ti, but prior to PROX OPS, (R-DOT=0)
  Perform RNDZ BREAKOUT

If during PROX OPS,
  Perform PROX OPS BREAKOUT

POST BREAKOUT RECONFIG
A6U   FLT CNTLR PWR - OFF
      |GNC 22 S TRK/COAS CNTL|
CRT   -Z (-Y) STAR TRK - ITEM 4 (3) EXEC (*)

      ON MCC call,
      |GNC 33 REL NAV|
      KU ANT ENA - ITEM 2 EXEC (no *)
      RNDZ NAV ENA - ITEM 1 EXEC (no *)

```

Figure 3-52.- Rendezvous OMS/RCS PRPLT PAD.

The first "bingo" quantity is the RCS level at which OMS interconnect is to be established. This is measured in RCS percent (1 percent RCS = 22 pounds of propellant), with the gauge (panel 03) counting down from 100 percent to 0 percent; typical interconnect bingo numbers are 50 to 60 percent. If the rendezvous phase is entered with an interconnect configuration already established, the value in this field is "N/A" for "not applicable."

The standard procedure is to interconnect first from the left OMS, with the total usage monitored on SPEC 23 (RCS), "OMS+RCS QTY" for "L." The units of this parameter are OMS percent (1 OMS percent = 129 pounds of propellant), counting up from 0 percent to a maximum interconnect of about 8.3 percent. Gauging is performed in the GPC by counting RCS jet pulses. Once the crew notices that a specified amount of L OMS propellant has been interconnected, they switch the interconnect to R OMS for another specified amount. Following that amount, the RCS system is manually returned to straight feed.

RCS quantities are then used to determine exit from DAP low Z mode; unlike the first set of RCS quantities (L or R only), this set includes FRCS as well as ARCS. Usually the ARCS values are the same as those provided in the first (top) RCS bingo specifications.

After an additional amount of RCS straight feed into NORM Z mode, the breakout bingo values are reached. Various options are available depending on where the crew is in the rendezvous profile.

The "post breakout reconfiguration" procedure performs the same essential steps as the standard post-rendezvous "disable rendezvous navigation" block, section 4.1.74 in the nominal rendezvous narrative.

3.8.4.2 Typical Propellant Consumption

The expected OMS/RCS consumption rates are provided in the CAP maneuver tables and consumables curves. Variations in preplanned operations will impact consumption and the following data is offered as an aid to estimating such impacts.

For propulsive maneuvers, the ΔV in ft/s converts to pounds of propellant via these equivalences: 1 ft/s costs about 22 lb through the OMS, 25 lb through the +X RCS, and about 35-40 lb through multiaxis RCS (about a third to a half out of the FRCS).

Once the final midcourse maneuvers are completed, the Orbiter begins manual phase, which involves nearly continuous thrusting.

The following propellant usages are derived from analysis of the 51-I and 51-L profiles:

	FWD(1 σ)	AFT(1 σ)	Total(1 σ)
Manual Phase (MC4+2 to V-BAR)			
Nominal	88(35)	159(40)	242(70)
Radar Fail	241(71)	289(93)	530(130)
V-BAR Approach (400 ft - 35 ft)	35(20)	65(20)	100(35)
35 ft Stationkeeping (LB/MIN)			
+V-BAR	0.20(0.2)	0.6(0.6)	0.8(0.7)
INERTIAL	0.59(0.39)	1.00(0.59)	1.58(0.94)
+V-BAR (LOW Z)	0.5	1.5	2.0
Align Maneuver (Per Axis) (Usually two reqd)	22(7)	39(16)	61(21)

These values represent smooth, skilled flying after proper training, with all sensors operable (except as noted).

Note: MMU reserve from 35 feet, no low Z, uses about total 257 (127), with 101 (52) from forward

Precise predictions will be prepared as required by the MCC.

3.8.4.3 Propellant Saving Techniques

In propellant-limited situations, RNDZ and PROX OPS may continue with special care to the following guidelines:

- Stay in verniers as long and as often as possible.
- To conserve FRCS, use TAIL ONLY control mode.
- Stay out of low Z as much as possible. Get R-DOT and out-of-plane situation under control (0.1 - 0.2 ft/sec) before 200 feet so that no inputs need be made until NORM Z can be resumed.
- Performing translations based on overhead window LOS to TGT, carefully observe Orbiter DB's prior to THC inputs; only make inputs when near center of DB.
- In controlling out-of-plane dispersions, start as early as possible, wait for the NODE to put in the pulses, watch the deadbands, and do not fight orbital mechanics effects.

3.8.5 Special Burns

RNDZ and PROX OPS require specialized applications of OMS/RCS propulsion capabilities.

3.8.5.1 RCS Axis-by-Axis

For axis-by-axis burns (section 3.6.3), RCS is used to manually achieve the targeted ΔV 's. The RCS BURN cue card is shown in figure 3-53, and specific call-outs of this procedure are defined in section 4.3.1.

```

TIG - 2:00
  OPS 202 PRO
    GNC ORBIT MNVR EXEC
  ✓TGT data loaded
  LOAD - ITEM 22 EXEC
  TIMER - ITEM 23 EXEC
TIG -0:30
  FLT CNTLR PWR - ON
  DAP TRANS: as reqd
  ROT: DISC/DISC/DISC
  DAP: A/MAN/NORM
TIG
  THC - Trim VGO's < 0.2 ft/s

  If VGO Z is neg, Z,X,Y seq,
  otherwise, X,Y,Z

  OPS 201 PRO
  DAP: A/AUTO/VERN
  FLT CNTLR PWR - OFF

```

Figure 3-53.- RCS BURN cue card.

This cue card may be entered from burn blocks where some operations (e.g., OPS 202 PRO item 22, 23 EXEC) may already have been executed. In that case do not repeat these steps.

The basis for this technique is described in section 3.6.3.

3.8.5.2 RNDZ OMS Burn

Specific call-outs of this procedure are defined in section 4.3.5. When performed for RNDZ maneuvers, the OMS burn (3-54) differs somewhat from the standard ORBIT OPS procedure. The KU antenna is moded to AUTO track if this is the Ti burn. Residuals trimming is specified to <0.2 ft/s. RCS engine select is explicitly selected as the default for the next burn. Resumption of UNIV PTG is explicitly called out. Nominal RNDZ DAP's are used.

```

√DAP A9, B6
  Install OMS 2/ORBIT BURNS cue cards
  (two) and OMS BURN MONITOR cue cards
  (two) (F7,F8)
CRT  OPS 202 PRO
      GNC ORBIT MNVR EXEC
      GNC SYS SUMM 2
      Load TGT data per burn pad
      LOAD - ITEM 22 EXEC
      TIMER - ITEM 23 EXEC
√Burn data per pad
C3   DAP: B/AUTO/VERN, NORM as reqd
      DAP TRANS: as reqd
      ROT: DISC/DISC/DISC

A1U  KU - AUTO TRACK (if reqd)
CRT  MNVR - ITEM 27 EXEC (*)
      When mnvr to att complete,
      DAP: A/AUTO/VERN

08   √OMS AND RCS config - Per Pad

TIG -2:00 **

F7/F8 FLT CNTLR PWR (two) - ON
      Perform OMS 2/ORBIT OMS BURNS
      Cue Card, then **

      THC - Trim residuals < 0.2 fps

F7/F8 FLT CNTLR PWR (two) - OFF
08   L,R OMS He PRESS/VAP ISOL (four) - CL
CRT  RCS SEL - ITEM 4 EXEC (*)
      Perform OMS TVC GMBL CK as reqd

      * If down arrow(s) or M(s), *
      * select good GMBL *

C3   DAP: B/MAN/NORM
CRT  OPS 201 PRO
      GNC UNIV PTG
CRT  √TGT ID, BODY VECT, P, Y, OM
C3   DAP: B/AUTO/VERN, NORM as reqd
      When in attitude, DAP: A/AUTO/VERN

```

Figure 3-54.- Perform RNDZ OMS Burn

After initiating the maneuver to burn attitude, the crew configures the propellant system pressurization valves. The OMS helium pressure/vapor isolation valves (A and B sides) are configured per instructions from the MCC. As part of the program to run on-orbit checks for redundant systems whenever possible, the A and B valves are configured so as to utilize the path with the least amount of flight usage. Most RNDZ OMS burns are classified as critical for mission success (the on-orbit NC2 burn is a crew safety maneuver because of potential for target impact if not performed) and therefore usually do require system redundancy during the burn. For a problem during execution, the crew completes the burn per downmoding instructions on the BURN PAD. At TIG-2:00 the crew powers on their flight control systems (the THC and RHC) and continues executing the burn. After exiting the cue card procedures, the crew uses the THC and manually trims out the residual ΔV 's by selecting the PRCS and the manual translational mode he/she desires (PULSE or NORM), and then deflecting the THC until the displayed values of velocity to go (VGO) are less than 0.2 ft/s. The crew then powers down the flight controller systems and closes the helium pressurization valves. If required by the MCC, the crew performs an OMS thrust vector control (TVC) gimbal check on the appropriate gimbal system(s). This is also a part of the in-flight redundant system checkout program.

3.9 OTHER SYSTEMS

3.9.1 Auxiliary Power Unit (APU)

The need to burn a leaking APU at the wrong time during a RNDZ can seriously affect procedures. Over an hour period, the force of about 4 pounds in the +Z direction can introduce a ΔV of 2 ft/s, causing extremely serious NAV impacts and trajectory dispersions late in the RNDZ. To avoid this, such a burn (if absolutely unavoidable) should be performed out of plane to negate possible down-range errors; post-Ti, this cannot be done without impacting sensors, so the ΔV hit must be swallowed and taken out at the midcourse burns. Note that it is unlikely that an APU will be burned during a RNDZ because if the leak is tiny, burning the APU can be delayed, and if the leak is large, it can be expected that the RNDZ will be terminated with the appropriate breakout, followed by APU burn and deorbit prep.

The acceleration is well below the limit of detectability by the IMU accelerometers.

For more details, see "APU Venting Effects on the Rendezvous - Day Trajectory," W. R. Britz, RSOC, September 1987.

3.9.2 PDRS

Track and capture training is normally conducted with translational rates up to 0.2 ft/sec and rotational rates of up to 0.3 deg/s simultaneously in all axes (pitch, yaw and roll). The training translational rate capability is generally considered to be unreasonable due to the potential hazards of attempting to grapple a translating target. In general, the translational rates would have been nulled by the Orbiter pilot during the terminal phases of the PROX OPS approach operations. The training rotational rates are considered to be reasonable. The flight specific rules governing any given flight will usually restrict these rates even further in order to prevent damage to the arm or the target.

RMS operations are mentioned in 4.1.41 in terms of use of the wrist CCTV. Problems which may frustrate PL recovery capability can be grounds for RNDZ delay, either at T_i or well before.

3.9.3 EVA

When an EVA and a RNDZ are occurring together, it is most important that the respective timelines be well coordinated. In particular, crewmembers may have to switch off tasks, since EVA normally involves two EVA crewmembers and one IVA crewmember and RNDZ (with or without RMS ops) involves two or three crewmembers.

The following items must be considered in preparing timelines:

- a. The pre-breathe in EMU's needs to be started about the same time as T_i .
- b. RMS is generally powered up immediately after T_i ; it can be delayed, but should not be planned to occur prior to T_i .
- c. Performance of the RR-FAIL procedures can get crowded by the EMU pre-breathe and/or the RMS powerup. Remember the RR-FAIL procedures take priority.
- d. Depending on the history of the RNDZ, the post- T_i NAV can be very critical to the successful completion of the rendezvous; therefore, two crewmembers should be dedicated full-time to RNDZ OPS on the flight deck during this phase.
- e. Selection of crewmember responsibilities (the flight crew does this) may require moving up or delaying activities from their nominal time slots.

Several other systems are impacted by joint RNDZ/EVA operations:

- a. Extended use of the PLB cameras may lead to their overheating. Since maximum possible EVA coverage is highly desired, the cameras will remain powered up long after the completion of the rendezvous. To shorten the total interval of camera powering, do not plan to perform PLB camera operations earlier than T_i .
- b. EMU problems can be a leading candidate for T_i delay.

3.9.4 IMU

The IMU is not used directly as a RNDZ sensor, but inertial attitude information from the IMU is processed by the RNDZ NAV software along with information from the RNDZ angle sensors. The three RNDZ sensors - radar, STRK, and COAS - measure angles in their respective coordinate systems, which are fixed with respect to the body coordinate system. The IMU supplies the necessary transformation from body coordinates to M50 coordinates. Therefore, any errors in the IMU attitude will result in errors in the incorporation of angular data into the RNDZ NAV filter. These IMU angular errors will appear to the filter as sensor measurement errors. IMU attitude errors as small as 0.01° will noticeably affect REL NAV.

An effort is made in the development of crew procedures to place an IMU alignment immediately before the beginning of the first navigation period (usually STRK) in a RNDZ profile. The need for an IMU alignment as close as possible to the beginning of the first STRK pass is due to the fact that IMU drift rate is large compared to STRK one-sigma expected bias.

A problem occurred on STS 41-C as a result of the way attitude processing is performed by the IMU redundancy management (RM) logic. With all three IMU's operating properly, the attitude RM logic should select the IMU with the smallest attitude error relative to the other two IMU's ("midvalue select"). If the errors between each of the three IMU's are nearly equal, then the RM may frequently change the selected IMU. This problem occurred on the first and second STRK passes of the first RNDZ of STS 41-C. This IMU switching appeared to the filter as a measurement noise of approximately 0.1° - much larger than expected from either the STRK or the IMU. Consequently, the filter believed the measurement and updated the Orbiter SV accordingly. Each time the selected IMU changed, a large update was made to the SV. To avoid these errors, one IMU is now deselected for the duration of each STRK pass, thus forcing RM to consistently send the lowest-numbered IMU's value to NAV.

SECTION 4

RNDZ PROCEDURE SEQUENCES

This section is the heart of the flight procedures rationale narrative, and is an entry point into the entire book. As each step is listed, described, and explained, in depth citations are given to specific background sections in chapter 3.

A standard last few REV's of the on-orbit rendezvous profile is narrated in section 4.1, where all the operations in the FDF Rendezvous book are described and explained. Differences with other rendezvous sequences are discussed, and in section 4.2 the features of rendezvous variations are described.

Specific rendezvous procedures sequences include both cue cards (described and explained in sec. 4.3) and off-nominal procedures (described and explained in sec. 4.4). In addition, procedures for post-rendezvous back-out (sec. 4.5) and for anytime break-outs (sec. 4.6) are referenced, with attention given to rationale for selection and execution.

Lastly, questions of procedures documentation are addressed. Relative motion plots are described in section 4.7, and generic documentation rationale for FDF is discussed in section 4.8.

4.1 STANDARD OPERATIONS FLOW

As a model for RNDZ, the updated and generalized version of the STS 51-L (Spartan-Halley) checklist is used. All steps are consistent with other current standard rendezvous profiles, such as in the Contingency Rendezvous book. Relative motion plots are given in figures 4-1, 4-2, and 4-3.

The following specific procedures are intended to be strung along the pages of the flight-specific FDF RENDEZVOUS CHECKLIST and thus comprise the "contents" referred to in paragraph 4.8 on FDF management. This book is entered from an explicit call-out in the CAP. Every 30-minute period is portrayed on a right-hand page and consists of a timeline with AOS, SR/SS, and DAP information, line by line action specifications or numbered block call-outs, and specific blocks themselves, each containing an integrated procedure; left-hand pages may contain burn pads or more numbered blocks referenced from right-hand pages or other blocks, or they may be marked "This Page Intentionally Left Blank". Also included on the 30-minute pages should be entries for expected MCC uplinks (e.g., voiced-up PAD's, MNVR CMD loads, COVAR MATRIX loads, etc.) and periodic notations of nominal range (kft) and range rate (ft/s) to target. The book's timeline ends with an explicit directive to return to a specific point in the CAP.

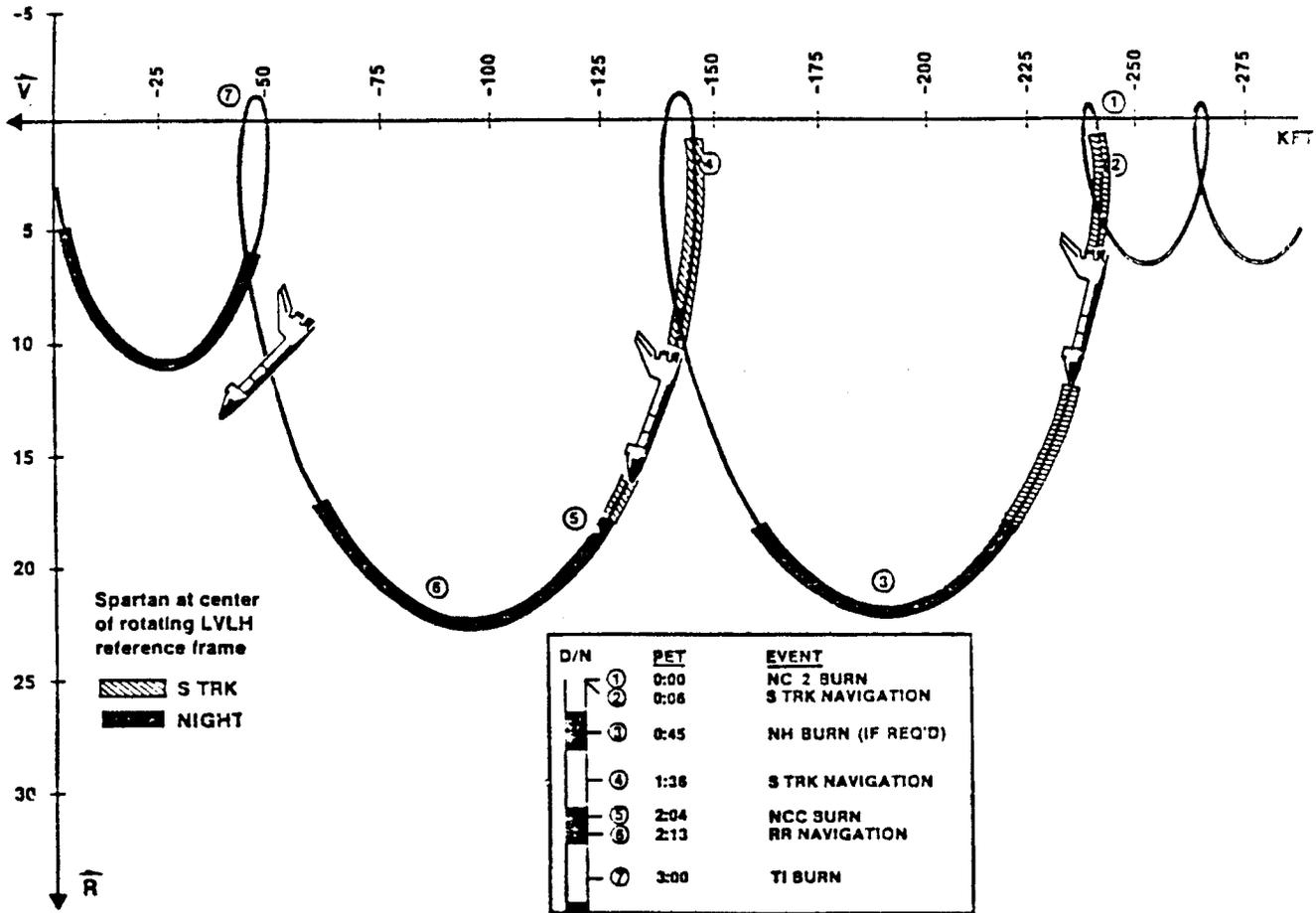


Figure 4-1.- Spartan rendezvous profile.

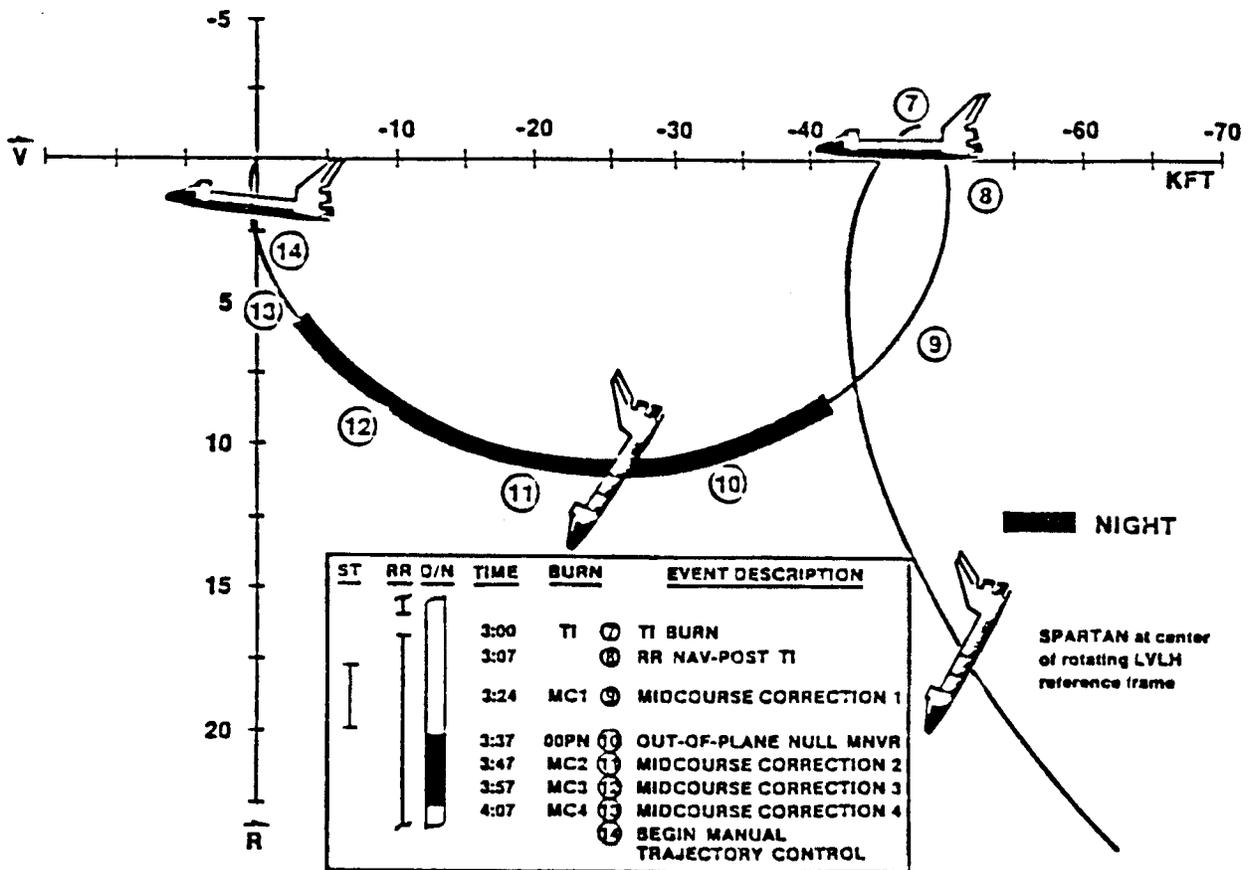


Figure 4-2.- Spartan rendezvous profile.

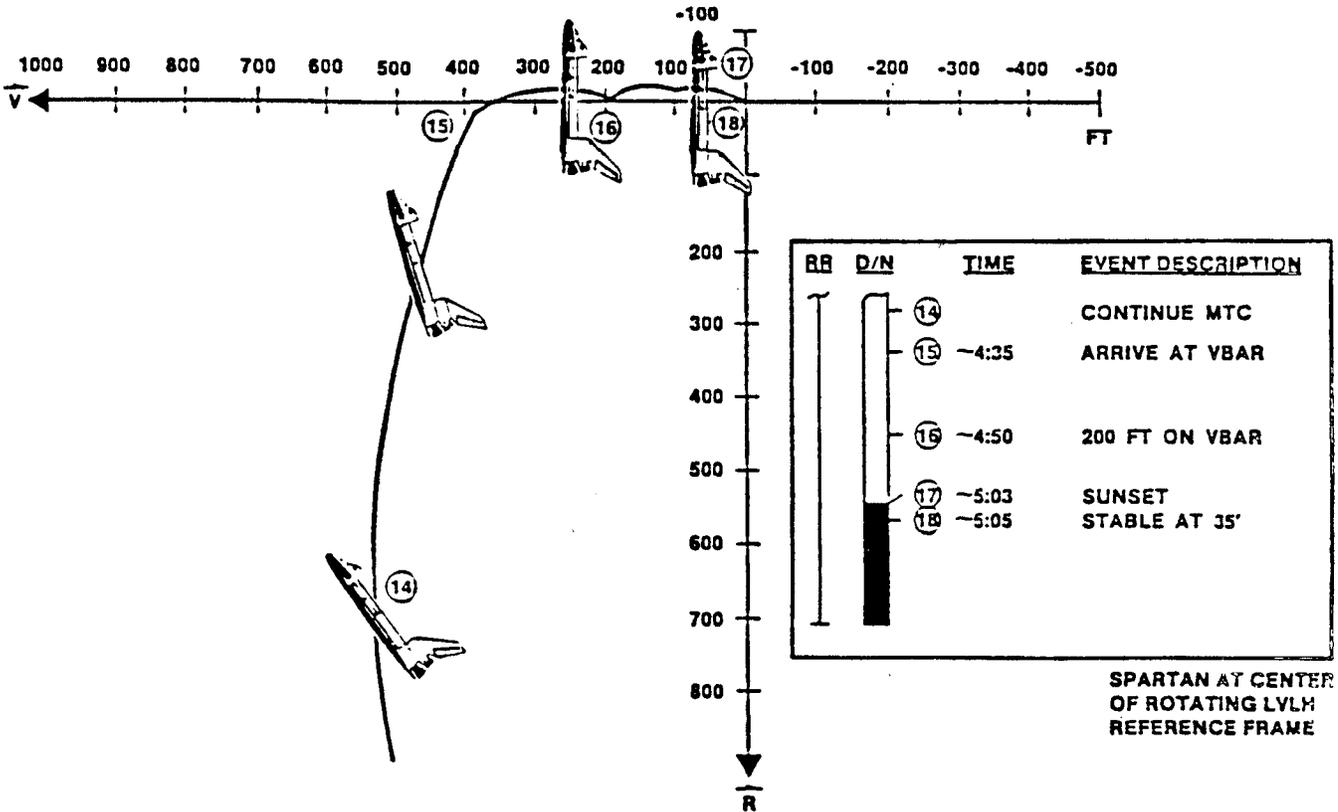


Figure 4-3.- Spartan rendezvous profile.

4.1.1 Configure DPS

(See section 6.1.1.)

4.1.2 Set SM Timer

The crew performs the step: "Set SM TIMER counting up to NC TIG (SPEC 2)."

The events that make up a RNDZ are not scheduled as individual items during an STS mission. The various procedures are timed in specific sequences relative to each other, to lighting conditions, or to target-referenced apogee/perigee occurrences. As such, the RNDZ timeline can, and should, be moved as a complete entity during a mission, if the need arises. To be as flexible as possible in supporting preflight mission planning and real-time mission operations, the RNDZ timeline was developed on a phase elapsed time (PET) scale. The reference time (00:00 = HH:MM) is usually defined as occurring at the NC burn. The crew utilizes the SM CRT timer in order to have an onboard timer set up as a reference for the RNDZ PET. The GNC computer timer is not used because one of the outcomes of targeting an onboard RNDZ burn using ORB TGT is that the GNC timer is automatically reset to count down to the burn ignition and would therefore overwrite the PET reference.

4.1.3 Configure Aft Flight Station

This block is shown in figure 4-4; this configuration can be done as the very first RNDZ action, ahead of the preceding two sections. The aft ADI is configured with its attitude coordinate system reference set to the LVLH coordinate reference. This reference is selected to support crew monitoring of Orbiter attitude and relative motion profile. The error and rate switches are set so that the crew has the most accurate display of data without truncating data. In these settings the error display is to $\pm 5^\circ$ and the rate to ± 1 deg/s. The sense switch is set to the -Z position since this is the axis parallel with the crew LOS as they monitor the TGT out the overhead windows and through the COAS.

To prepare for subsequent operations the crew installs the COAS in the -Z (window 7) position and unstows and installs the cue cards needed for RNDZ.

```

A6U  ADI ATT - LVLH
      ERR - MED
      RATE - LO
      SENSE - -Z

R13  ✓KU ANT - GND
A1U  ✓PWR - ON
      KU MODE - RDR PASSIVE
      RADAR OUTPUT - HIGH
      CNTL - MAN SLEW
      CNTL - PNL
      SIG STRENGTH sel - KU
      SLEW RATE - as reqd
A2   DIGI-DIS SEL - R/RDOT
      X-PNTR SCALE - X1

CRT  SM ANTENNA
      ITEM 7 EXEC (*)
      NOTE
      SELF TEST runs about 3 min

A1U  ✓KU SCAN WARN tb - gray
      ✓TRACK tb - gray
      ✓SEARCH tb - gray
A2   ✓RANGE - 888.8
CRT  SELF TEST - ITEM 7 EXEC (no *)
A2   DIGI-DIS SEL - EL/AZ

A1U  KU MODE - COMM
      ✓KU - MAN SLEW
      KU CNTL - CMD
      Install -Z COAS
      Install RNDZ OPS Cue Card (two)
      Install PROX OPS Cue Card

```

Figure 4-4.- Configure aft flight station for RNDZ.

4.1.4 Ku-Band Self Test

(See section 3.3.4.4.)

4.1.5 NSR burn (as required)

For reasons stated in section 2.9.1.3, an NSR burn sometimes is performed prior to the last NC burn. Although this profile did not have one, some ground-up rendezvous will and all long-duration, on-orbit separation/rendezvous profiles probably will.

The burn is performed just like a standard RNDZ OMS BURN (fig. 3-54), except that postburn the RCS ENG SEL is not automatic, and the UP is selected to TRACK.

translational pulse sizes, rotational discrete rates, ATT DB, and jet option selection.

Translational pulse size of 0.10 ft/s in DAP A gives the coarse control and 0.05 ft/s in DAP B gives the fine control necessary to effectively trim out the targeted translational burns, and also control the trajectory during the manual final phase corrections.

Rotational discrete rates are set to 0.2 deg/s (the standard Orbiter maneuver rate) except for DAP B primary RCS (NORM) which is set to 0.5 deg/s in order to maneuver quickly if necessary.

ATT DB sizes are based on several interrelationships. First, it is desirable to have the NORM ATT DB as large as possible because the primary RCS (PRCS) uses large amounts of propellant in tight ATT DB's. Secondly, to provide accurate pointing for sensor acquisition and crew monitoring, the ATT DB needs to be as small as is practical in all DAP configurations and for all jets. Lastly, in order to keep from constantly initiating small but costly attitude maneuvers back to attitude after performing PRCS translations, the NORM ATT DB should be no more than twice as large as the vernier ATT DB. This is due to the fact that the DAP phase plane logic initiates a DISC rate maneuver back to attitude when the Orbiter attitude errors exceed twice the specified ATT DB. In solving for the ATT DB values, a reasonable solution was a 1.0° VERN ATT DB and a 2.0° NORM ATT DB.

The jet option selection is set to 1 (full up nose and tail control) to provide coupled ROT's when on the PRCS. Either nose- or tail-only options introduce noticeable translational delta velocities when operating on the PRCS.

4.1.9 Perform NC (Phasing) Burn

The NC burn is calculated to place Ti burn position 8 n. mi. (48,600 feet) trailing the TGT. To effectively move the downrange position of Ti without affecting its altitude, the NC burn is executed at an integral multiple of the orbital period prior to Ti.

A typical NC burn block is shown in figure 4-5. The NC burn is performed using TIG and ΔV 's that have been ground calculated and voiced to the crew (a command load is also sent up to MM202). NC TIG is usually one or two REV's prior to Ti.

In the case of a ground-up RNDZ, NC is usually posigrade, raising relative perigee and thereby decreasing the phasing rate. The major driver for temporal placement of the NC burn is the length of the crew workday on the day of RNDZ. Therefore, NC is usually done one REV before Ti to shorten the total time period required to perform the RNDZ.

For on-orbit rendezvous profiles, however, the NC burn usually is retrograde, lowering relative perigee and thereby increasing the Orbiter closing rate on the TGT. This is the case because the Orbiter is either drifting

```

      GNC UNIV PTG
      CNCL - ITEM 21 EXEC
      OPS 202 PRO
      GNC ORBIT MNVR EXEC
CRT   Load TGT data per pad
      LOAD - ITEM 22 EXEC
      TIMER - ITEM 23 EXEC
      ✓ Burn data per pad
C3    ✓ DAP: A/AUTO/VERN
      ✓ DAP ROT: DISC/DISC/DISC
      ✓ DAP TRANS: As reqd
CRT   MNVR - ITEM 27 EXEC (*)
TIG -2:00 **
      Perform EXECUTE RCS BURN (Cue Card, RNDZ OPS)

```

Figure 4-5.- Perform NC burn.

farther behind the TGT or just slowly closing. NC is usually done two REV's before T_i to reduce the ΔV (and therefore propellant) required, if time is available.

Depending on the total velocity to burn, the MNVR will be executed using either the RCS or the OMS. The OMS guidance system has been developed such that with 2 seconds remaining in an OPS 202 burn, a countdown mode is entered, and the software no longer iterates on the required remaining ΔV to burn, but rather calculates when to terminate the burn. This can result in substantial burn residuals that the crew needs to trim manually. In addition, the system configuration required for an OMS burn is more complicated than for an RCS burn and is only exercised when the velocity to be burned is large enough to warrant the extra system manipulation. If the preflight analysis has shown the burn to require use of the OMS, the procedure will nominally be included in the RNDZ checklist. If in-flight trajectory dispersions result in NC being performed using the OMS, the crew would use the RNDZ OMS BURN procedures (sec. 3.8.4.1).

For either translational control system, the initial onboard setup by the crew is the same.

Depending on the profile, the crew may cancel the UNIV PTG option in effect (via ITEM 21). This is done to prevent unnecessary attitude maneuvers after the completion of the burn operations. After the NC burn, the crew will need to maneuver the Orbiter to a TGT TRK attitude to support STRK acquisition of the TGT. Canceling the UNIV PTG option ensures that the Orbiter will not begin maneuvering to the pre-NC burn attitude, once the burn is complete and OPS 201 is reentered.

The crew transitions the GNC GPC's to OPS 202 for burn execution and enters the burn targeting data per the uplinked pad. The data is loaded and the GNC burn countdown timer is initiated. The onboard calculations for resulting burn duration, apogee, perigee, and attitude are verified by comparison

with the uplinked data. The crew verifies that the DAP is configured as required for an attitude maneuver, and then initiates the maneuver via ITEM 27 execution.

The remainder of the burn procedures differ depending on the translational system to be used for the burn.

RCS NC BURN: At 2 minutes prior to TIG, the crew begins the procedures specified for an RCS burn on the RNDZ OPS cue card (sec.3.8.5.1). It should be noted that the cue card procedure was written for an RCS burn which is performed in a random attitude, as is the case for the midcourse correction (MC) burns. Since the NC burn is done in single-axis burn attitude, several of the cue card steps are done early to allow time for the maneuver to attitude, so these steps need not be repeated at TIG-2:00.

OMS NC BURN: See section 3.8.5.2 for rationale.

Before returning to OPS 201 and continuing RNDZ operations, the DAP is configured to be under VRCS control so that subsequent attitude maneuvers are not begun by the PRCS.

4.1.10 Initiate -Z Target Tracking

After the NC burn is complete and the GPC's are back in OPS 201, the crew begins a maneuver to track the TGT with the -Z axis for -Z STRK TGT acquisition or with the -Y STRK, if the -Z STRK is known to be failed. Since NC was performed just prior to orbit noon, lighting conditions after the burn should be favorable for TGT acquisition (fig. 4-1). The maneuver to track attitude is done on PRCS in DAP B to utilize the 0.5 deg/s rate and arrive in track attitude as quickly as possible and begin taking sensor data; return to DAP A VERN when maneuver is completed.

4.1.11 First STRK Acquisition

(See section 3.3.2.1.)

4.1.12 Configure NAV for STRK data

The NAV software is verified to be in proper configuration for processing of STRK data. Initial setup ensures that the source of angle data to be incorporated is the STRK's, the uplinked propagated SV is selected as input to user parameter processor (UPP) while the filtered SV is being sent the initial sensor marks in case of erroneous or large updates, and that the angles are inhibited from AUTO incorporation in order to allow crewmembers to verify proper target lock-on.

4.1.13 STRK NAV Data Acceptance

The SV selection is made when the SV POS update is less than 1.0 K ft. At STRK acquisition ranges it is felt that the Orbiter body pointing vector will be locked on to the TGT within the Orbiter ATT DB at this point. Typical error is about 1000 feet at 30 miles. Disregard SV U/D VEL.

The angle residual (RESID) value is a measure of the angular error between the predicted LOS to the target and the detected LOS. A star will have an angular rate of 0.5° per 8-second cycle, which is 10 times the threshold for rejection of marks. If the STRK has locked on to the TGT and Orbiter is in TGT track attitude hold, the RESID value need not be zero, but should remain constant. It is not important that the value of the RESID is less than 0.05, but that it remains at a constant value ± 0.05 . A constant RESID value indicates that the predicted state for the target is slightly offset from the actual. Changing values indicate that the STRK has locked onto an object that has an angular rate with respect to the predicted target position, such as a star or debris in the vicinity of the Orbiter. The value of 0.05 was selected as the criteria for determination of lock-on based on estimations of system noise and granularity.

For the usual Orbiter attitude during this phase (nose to Earth), if the STRK locks on to a star, the affected residuals will depend on which STRK is active. For the Z STRK, the H RESID will change, and for the Y STRK, the V RESID will change. Such behavior by the residuals is positive proof that star lock-on has occurred.

If the 0.05 criteria is met for four NAV cycles (four to ensure repeatability) the target lock-on is assumed to be correct, and the software is set to automatically incorporate data marks into the NAV filter that update the Orbiter FLTR SV once the crew selects AUTO.

If the filtered minus-propagated SV changes by more than 40 kft during a single STRK pass, the STRK data is considered bad and has corrupted the filtered state. See section 4.1.15.

4.1.14 SV Selection

In order to have a consistent SV input to UPP during the TGT acquisition, the propagated SV remains selected until the filtered SV "settles down," and no large updates are seen. Once again, analysis has shown that for STRK NAV when the position updates to the SV are less than 1.0 kft, and more than nine marks have been accepted into the filter, the filtered SV has converged to the point where it can be selected as the source of Orbiter SV data in UPP.

The propagated SV will be selected for the UPP until the beginning of the first relative TRK interval. The filtered SV will be selected:

- a. If 10 STRK measurements have been accepted with the last SV position update less than 1.0 kft

- b. If 10 RR measurements have been accepted with the last SV position update less than 0.3 kft.
- c. If three COAS measurements have been accepted

Accepting 10 STRK or RR measurements prior to selecting the filtered SV for the UPP prevents filter vector transients from reaching the UPP. Also, if bad measurements are incorporated into the filtered SV (e.g., tracking a star with the STRK, tracking with a side lobe with the RR), this delay allows the crew to take appropriate action to prevent use of the corrupted state. Because COAS processing takes longer, only three marks are taken prior to selecting the filtered state vector. (Ref: Charles Stark Draper Lab Memo 10E-94-07, appendix A; Apr. 19, 1984.) Analysis shows that most pointing error has been removed after nine marks.

4.1.15 Off-Nominal SV

Analysis has shown that the initial SV data should not be in error by more than 40 kft and, therefore, if the updates to the SV exceed 40 kft in a single STRK data pass, lock-on was probably false and the data should be erased (another alternative is an IMU is failing). In this case, the propagated SV is reselected as the source of data to UPP. The sensor data is inhibited from being incorporated into NAV any further, and the filtered SV is overwritten with the unpolluted propagated SV. The STRK is then commanded to break lock with the TGT it has been tracking, and the acquisition process is begun again.

4.1.16 End STRK Pass

(See section 3.3.2.2.)

4.1.17 Perform NH Burn (if Required)

To control the differential altitude between the Orbiter and the TGT on the day of RNDZ, an NH MNVR may be included in the RNDZ sequence (fig. 4-6). Often, the differential altitude between the Orbiter and the TGT has been properly adjusted prior to entering the RNDZ procedures and an NH burn is not required. If, however, the projected T_i relative altitude differs significantly from premission design, the NH burn will be performed. Should an adjustment be required, the rationale and procedures for burn execution are the same as for the NC burn.

In the extremely unlikely event that $\Delta V T > 6$ ft/s, perform NH using the RNDZ OMS BURN cue card. If the ground solution shows >2 ft/sec from the FRCS, a +X RCS burn will be performed.

```

OPS 202 PRO
  GNC ORBIT MNVR EXEC
CRT   Load TGT data per pad
      LOAD - ITEM 22 EXEC
      TIMER - ITEM 23 EXEC
      ✓Burn data per pad
TIG -2:00 **
      Perform EXECUTE RCS BURN (Cue Card, RNDZ OPS)

```

Figure 4-6.- Perform NH burn.

4.1.18 Configure for Radar Target Acquisition

(See section 3.3.4.5)

4.1.19 Target NCC Burn (Preliminary)

The NCC burn (fig. 4-7) is aimed at the Ti point, 48.6 kft behind and 1.2 kft above the target, and in plane. The trailing distance is chosen based on expected trajectory dispersions and RR acquisition limits. The delta height is chosen empirically to reduce MC2 TIG slips and thus maintain manual phase lighting. Being in plane with the target at Ti allows the planar error to be nulled in a propellant-efficient manner.

Establishing a 225° transfer from NCC to Ti was based on several factors. With Lambert targeting, 360° transfers will not control delta altitude or out-of-plane errors, and 180° transfers will not control planar errors. Waiting as long as possible (typically until orbital sunset) allows maximum time for relative NAV to incorporate sensor data. A compromise of 225° was selected because it controls phase, delta altitude, and out-of-plane errors; it is close to orbital sunset to allow sufficient STRK data to be incorporated; and it is large enough to be propellant efficient.

The theoretical basis for out-of-plane control is described in section 2.9.2.

Prior to the beginning of the second STRK data pass, a preliminary calculation of the NCC burn is performed using the onboard Orbiter targeting software. As is the case for the preliminary solution for all the onboard calculated burns, this initial targeting exercise serves two purposes: it gives a very early indication of the onboard estimate of burn ΔV 's, and it begins the GNC GPC timer counting down to the burn TIG.

```

..Final Solution.....
. OPS 202 PRO
. ✓ENGINE SELECTION CORRECT .
.....
CRT ✓SV SEL correct

      GNC 34 ORBIT TGT
TGT NO - ITEM 1 +9 EXEC
✓TGT Set data:
  T1 TIG = BASE TIME - 0/00:56:18
  EL      +0
  ΔT      +56.3
  ΔX      -48.60
  ΔY      +0
  ΔZ      -1.20
COMPUTE T1 - ITEM 27 EXEC

Note solution

Final solution
.....
. If > 40 marks in current sensor pass and
. SV UPDATE POS < 0.5, Burn FLTR soln
. If FLTR within ground solution limits, Burn
. FLTR soln
. If PROP within ground solution limits, Burn
. PROP soln
. If none of the above, Burn ground soln EXT ΔVs
.....

```

Figure 4-7.- Target NCC burn.

Before performing the targeting, the crew verifies that the SV source for the calculations is as expected. Nominally the FLTR SV will be selected, but depending on the circumstances (mainly, sensor failures time history), the PROP SV may still be the prime source of the UPP state data. The crew and ground need to be aware of the source of the burn solution.

The TGT set for the NCC burn is called up by entering the appropriate TGT number, and then the I-loaded data for the TGT set is verified. The TIG displayed in MET is verified to be equal to the base time as loaded earlier (see 4.1.7) plus the relative time stored as part of the TGT set. The elevation (EL) in degrees, the delta time in minutes, and the targeted offset position in k/ft are all verified to be the correct values. The crew then computes (ITEM 27) the burn solution. If any of the data displayed is not as expected, the crew overwrites the affected data entry, loads (ITEM 26) the new value into memory for that TGT set, and recalls that TGT set to confirm the proper data was saved before computing a solution. This is done because the burn calculation is based on the data stored in memory for the displayed TGT set, not on the displayed data itself. For informational purposes the crew notes the burn solution in their checklist.

Because the REL NAV systems of the Orbiter can provide the most accurate and current states for the Orbiter and TGT, orbit targeting (SPEC 34) is utilized to compute MNVR's on the day of RNDZ, beginning with the first MNVR (NCC). Orbit targeting is designed to schedule MNVR's relative to a

specified base time. By doing so, the entire manéuver plan can be shifted in time by updating just one I-load rather than every MNVR target set. Typically, the initial base time is set to Ti TIG near orbital noon. Since orbit targeting has no lighting software and the GRID/SPOC computer currently cannot support this computation, the ground will provide the initial base time.

4.1.20 Second Star Tracker Target Acquisition

The procedures used in the first STRK acquisition (sec. 3.3.2.1) are slightly different from all subsequent acquisitions due to the fact that the first acquisition had no history of sensor data taking. In the initial acquisition, the covariance matrix was configured with wide data acceptance criteria and the propagated and filtered SV's were identical. In subsequent acquisitions, the covariance and the filtered SV have been updated based on sensor data. Analysis of valid TGT lock-ons can therefore utilize more sources of data to determine accurate and valid TGT acquisition. Special procedures are also needed if the -Y STRK is being used. Note also that on entering this box, the SV SEL (ITEM 4) is now FLTR, not PROP, so that check statement (fig. 3-13) is eliminated.

The STRK procedures in sections 4.1.20, 4.1.21, and 4.1.22 are essentially identical to the STRK procedures for RR fail post-Ti, as described in section 4.4.2.

4.1.21 STRK Configuration

All of the configuration setups are the same as for the first STRK pass (sec. 3.3.2.1).

4.1.22 REL NAV Management

Because the filtered SV now has some incorporated sensor data, the filtered SV and the propagated SV now differ and the covariance has been shaped based on the data acquired. The procedures for acceptance of subsequent sensor data utilize these differences in the determination of valid lock-on condition.

If the RESID values pass the 0.05 test as in the first acquisition, the data is not immediately assumed to be valid as in the first acquisition. If the RATIO is confirmed to be less than 1.0, the data being accumulated by the sensor is within error boundaries as defined by the covariance and is assumed good. The FLTR SV which was used as the initial estimate for TGT lock-on has been proven to be correct since a valid lock-on occurred (see section 3.4.2.2) and it is then "saved" away in the PROP SV location (via a "FLTR TO PROP - ITEM 8 EXEC" line). This is done to provide a proven backup SV should the subsequent sensor data corrupt the FLTR SV. After the SV transfer, the NAV filter is configured to automatically accept STRK angle measurements.

If, however, the RATIO value is greater than 1.0, the crew now has several actions to take. The first assumes that the covariance has inappropriately tightened its data acceptance criteria thereby causing the data to result in a RATIO greater than 1.0. By reinitializing the covariance to the last uplinked values (usually those sent for the beginning of the RNDZ), the acceptance criteria is opened up. This is done via a "COVAR REINIT - ITEM 16 EXEC" line.

At this point, the crew begins their data analysis again by verifying RESID V and H VALUES, as well as rechecking the RATIO to verify it as now less than 1.0. If it is, they perform a FLTR TO PROP transfer and begin AUTO data collection as is called out in the first part of the "If" statement. If not, perform the "problems" steps specified in section 3.4.1.3 (on the checklist this will now be items 2 and 3, "FORCE 3 Angle Marks" and "PROP TO FLTR - ITEM 9 EXEC").

4.1.23 State Vector Management

(See section 4.1.15)

4.1.24 Target NCC Burn (Intermediate)

After approximately 70 data marks (about 10 minutes, when SV updates are small and stable) of STRK data, the NAV filter should "settle down" and the subsequent updates to the FLTR SV should be small. At this point, the crew calculates an intermediate solution for the NCC burn to get an early indication of the impact the new STRK data is having on the FLTR SV, and therefore on the burn solution. To calculate a valid burn solution, the crew must first recall the TGT set, even though the TGT set data still appears on the screen from the preliminary targeting. If a burn solution is requested and the displayed relative state values (ITEM's 6 to 12) are non-zero, orbit-targeting software will calculate a new solution, but will assume that the displayed relative state values currently in memory are still correct. Recalling the TGT set blanks out the previous values so that a new solution for the burn is computed.

If at this time the total ΔV to be burned appears to be approaching or greater than 6 ft/s, the crew should perform another burn calculation early enough to support a maneuver-to-burn attitude and OMS system configuring. If the crew waited until TIG-4:00 to do their final burn solution as in the standard timeline, it would be too late to maneuver to attitude and still get NCC performed in time.

4.1.25 End STRK NAV

(See section 3.3.2.2)

4.1.26 Target NCC Burn (Final)

At 4 minutes prior to TIG, the final solution for the NCC burn is calculated (fig. 4-7). If the total ΔV to be burned was estimated at greater than 6 ft/s during the intermediate solution, the final burn calculation should be accomplished earlier (approximately TIG -10:00) in order to allow time enough to maneuver to OMS burn attitude.

Before executing the final onboard calculation, the crew transitions the GPC's to OPS 202. This halts data collection and ensures that the SV used for calculating the final burn solution will not be updating from the time the final solution is calculated until the burn is executed. This is important for the NCC and Ti burns because ΔV comparison is part of the decision process that the crew goes through in determining whether or not to burn the onboard solution. Remember that even though the software is configured for AUTO (ITEMS 17, 20, or 23) in OPS 202, sensor data is not incorporated into the FLTR SV unless an ITEM 3 (MEAS ENA) has been executed. The ITEM 3 is only valid in 202; it is an ILL ENTRY in 201.

The crew recalls the TGT set and calculates the final burn solution. At this point the crew has several independent NCC burn solutions and must decide which solution is the best to execute.

Note that all onboard MNVR's will be targeted at least twice: once soon after the previous maneuver, then again shortly before TIG (as late in the NAV pass as possible).

The intent in choosing 4 minutes before TIG (as opposed to 6, 8, or 10 minutes) as the time to do the final targeting solution was to have a time as close as possible to the burn (more sensor marks are taken to improve the state), but far enough away so that the crew doesn't have to rush to get the burn off.

Note that verification of RCS engine selection should have been done prior to entering this box (i.e., before leaving MM 202 after the last burn). If ORB TGT'ing has already been executed, a change on the left side of ORB MNVR EXEC causes a Lambert burn to downmode to external ΔV . If this occurs, the crew can recall and recompute the TGT set on ORB TGT'ing. If not, the crew can proceed with the axis-by-axis burn with any engine selected. In that case, since the VGO's will be correct and that's all the crew is "flying to," the only real difference is that for an OMS selection the EXEC will flash (it can be ignored) and the TGO and burn attitude will be wrong (they should be ignored also).

4.1.27 Solution Selection

The hierarchy of priority for burn solutions has the FLTR SV solution as the most desirable source of burn calculation, followed by the onboard PROP SV solution and the ground calculated burn delta velocities. If the onboard FLTR SV has had greater than 40 STRK data marks incorporated during the pass just completed, and if the updates to SV position are less than 0.5 kft for

the last 4 marks, the FLTR SV has operationally converged and is the best source of relative state data, so it is therefore used for the NCC burn execution. After 40 STRK marks, the major transients in SV convergence are over and the filtered result is more accurate than the SV used for TGT acquisition. During the first 40 marks, filter performance can actually result in SV divergence leading to degraded burn solutions. The marks are specified to have occurred during the sensor pass just completed, rather than the earlier STRK pass to ensure that the data is current, and to serve as a rough order of magnitude data validation.

Note: Four consecutive marks with SV position errors less than 0.5 kft was added to this criterion to eliminate transient effects and to ensure the filter state was stable. (Ref: Charles Stark Draper Lab Memo 10E-84-03, STS-13 Rendezvous Nav Study)

Obtaining and incorporating COAS NAV marks is a time consuming manual task. Forty marks in a single COAS pass is unrealistic. Furthermore, statistical studies show that after the first few COAS marks, updates to the filtered state are somewhat random and do not significantly contribute to the improvement of the relative state. Therefore, since the COAS can never meet this criterion of sufficient NAV data, this rule does not apply to it.

If these criteria are not met, the burn solution based on the FLTR SV is compared with the ground computed ΔV 's. If FLTR SV and ground solutions agree on an axis-by-axis basis to within \pm the LIMITS values given in the NCC BURN SOLUTION pad, the burn is executed using the FLTR SV calculations. These limits are the root-sum-squared differences of the premission-calculated 3-sigma values for the ground and onboard NCC burn ΔV 's solutions.

The onboard filtered solution, even without sufficient relative NAV data, will be as good or better than the propagated or ground solutions because it may have some REL NAV data incorporated plus any IMU sensed ΔV 's since the ground initialization SV. Agreement with the ground solution serves as a gross quality check for the onboard solution and, therefore, only needs to fall within the 3-sigma comparison limits.

Next in priority for usage is the onboard PROP SV solution. If the FLTR SV solution passes neither of the above criteria, the PROP SV solution is compared to the ground solution and is executed if it agrees within the limits.

The onboard propagated solution will be better than the ground solution because it has been computed on either the ground initialization state vector plus any IMU sensed ΔV 's, or a filtered SV containing REL NAV data from a previous sensor pass that had been saved via a FLTR to PROP transfer. Agreement with the ground solution serves as a gross quality check for the onboard solution and, therefore, only needs to fall within the 3-sigma comparison limits.

As a last resort, if none of the above criteria are met, the crew manually loads and executes the ground solution for the NCC ΔV 's.

4.1.28 Execute NCC Burn

Unless the NCC burn velocity has increased to the point where an OMS burn is required, the crew executes the burn using the PRCS and trimming out the required ΔV 's while staying in the TGT TRK attitude. The detailed procedures for burn execution are included on the "Execute RCS Burn" cue card (see sec. 4.3.1).

4.1.29 Maneuver To -Z Track Attitude From -Y STRK (Off-Nominal)

If the -Y STRK has been in use for TGT data taking, the Orbiter will be in TGT track attitude with the -Y STRK pointing at the TGT. Since the next sensor to acquire the TGT in the profile sequence is the RR, and since its boresight axis is along the -Z axis, the Orbiter will need to be maneuvered to a -Z axis TGT tracking attitude. Although use of the -Y STRK was terminated earlier, the maneuver is not initiated until the NCC burn execution is complete to avoid complication during the burn (the burn normally occurs just after sunset).

4.1.30 Perform Radar Lock-on

During the radar acquisition (fig. 4-8), the Orbiter attitude is such that the -Z body axis is pointing at the estimated TGT position. Since the RR system boresight ($AZ = EL = 0$) is fairly closely aligned with the Orbiter -Z, the RR AZ and EL angles should be nearly zero if the main beam has acquired the desired TGT. If this is not the case, the RR may have acquired via one of the beam side lobes, and the crew should break track and allow the system to reacquire. If no lock-on has occurred by $R = 60$ kft, the crew performs the RR AUTO TRACK ACQ cue card (sec. 4.3.2).

4.1.31 Initiate RR NAV

After the RR hardware has indicated a TGT lock-on, the compatibility of the data with the NAV state is confirmed by monitoring the RATIO. Unlike with the STRK, in a typical RNDZ environment, it is highly improbable that the RR could be locked on to anything other than the desired RNDZ TGT. Therefore, it is not a question of determining a valid acquisition, but rather of data compatibility. See figure 4-8.

instead of a side lobe. Residual ratios less than one indicate that the measurements, if accepted by selecting AUTO, will not be edited by the NAV filter.

Recall that in the condition where $RATIO > 1.0$, performance of the specified steps is continued until the condition fails, then return to top of the conditional statement, where $RATIO < 1.0$ is performed and procedure is continued. Do not perform all the steps by rote, but exit as soon as one of the steps has forced $RATIO < 1$. See next section.

4.1.32 Off-Nominal RR NAV

If the RATIO happens to be greater than 1.0, there are two cases to consider. In the first, there has been a valid STRK acquisition previously in the RNDZ, and in the second, the RR data is the first onboard sensor data to be acquired.

If previous STRK data has been incorporated into the FLTR, the high RATIO value may be the result of the covariance having converged too tightly; therefore, the first crew action is to do a COVAR REINIT. If the RATIO is still too high, the crew questions the validity of the FLTR SV by looking at the past usage of that state. If the NCC burn was performed using ΔV 's calculated using the FLTR SV (see 4.1.27), the SV is assumed good. The FLTR SV is copied into the PROP SV, and three marks are forced into whichever parameter(s) has the high RATIO value. If the RATIO remains above 1.0 for any of the three radar parameters or if the FLTR SV was not used for NCC, the FLTR SV is overwritten with the PROP SV and acquisition is attempted again.

With no previous STRK data in the FLTR SV, the covariance is already open and the FLTR and PROP SV's are the same. Therefore, the only alternative to try to bring down the RATIO is to force three data points into the NAV filter.

The above discussions for RATIO greater than 1.0 apply easily when all three radar parameters have high RATIO values. If one or two parameters only are above the 1.0 limit, the related crew action is based on the overall complexion of the RNDZ. Have there been radar hardware problems/glitches? Was there a lot of noise in the STRK data? Are the RATIO's for two of the parameters near zero while one parameter fluctuates?

For example, if two parameters have near zero RATIO's while one parameter has greater than 1.0, it may be prudent to do a FLTR TO PROP transfer and configure the two "good" parameters to AUTO incorporation into NAV and see if their impact on the FLTR SV causes the ratio of the third parameter to drop below 1.0. For noisy data that sometimes has RATIO values greater than 1.0, that procedure may also be advisable, although on MCC call it may be possible to put all three parameters into AUTO and allow the NAV software to reject the out-of-limit data takes while filtering the remainder of the

data. The Kalman filter and the sizing of the covariance should keep damaging data out of the FLTR SV. These conditions have never been observed in flight.

4.1.33 Target Ti Burn (Preliminary)

A preliminary solution for the Ti burn is calculated (fig. 4-9). The Ti TGT set is I-loaded as TGT set no. 10. Since the Ti TIG was selected as the reference time for orbit targeting, the T1 TIG time displayed should equal base time. The transfer time is equal to 320° of orbital travel and the target point is a TGT intercept.

```

GNC 34 ORBIT TGT
CRT  TGT NO - ITEM 1 +1 0 EXEC
    ✓TGT Set data:
      T1 TIG = BASE TIME
      EL      +0
      ΔT     +80.1
      ΔX      +0
      ΔY      +0
      ΔZ      +0
    COMPUTE T1 - ITEM 27 EXEC

    Note solution in pad.

```

Figure 4-9.- Target Ti burn.

Ti TIG is chosen so that MC4 occurs 3 minutes after orbital sunrise. Typically, this equates to 3 minutes prior to orbital noon for Ti TIG.

The 320° transfer to intercept is a byproduct of placing orbital sunrise 3 minutes prior to MC4, protecting an STRK pass post-Ti, and requiring zero inertial line-of-sight rates at manual control initiation.

By performing Ti above the V-BAR, MC2 time slips are decreased because the expected dispersion ellipse begins to line up, or "point," to the TGT.

Ti is targeted to intercept, rather than any offset point (e.g., 1000 ft down the TGT V-BAR), because this allows the selection of a trajectory which has the crucial quality of near constant inertial LOS rates to TGT for terminal phase. This characteristic provides a "fly-to" target (especially for radar fail) and this is deemed a mandatory piloting aid.

The ground solution limits referred to in the Ti BURN PAD are the RSS of the preflight predicted ground solution errors and the predicted 3-sigma onboard solution errors, and represent the maximum expected difference between the final onboard solution and the in-flight ground solution. If, for some reason, the onboard solution is suspect, the limits will be used to evaluate the agreement between solutions.

4.1.34 Target Ti Burn (Intermediate)

After the NAV filter has converged (>40 marks accepted and SV position updates <500 ft), an intermediate solution for Ti is calculated. Remember that the target set must be recalled in order to get a valid burn solution. As with earlier burns, if the total ΔV to be burned is large enough, the crew may be instructed to execute the Ti burn using the OMS. Additionally, if the burn is less than 4 ft/s, the crew may be instructed to perform the burn by burning out the velocities axis by axis while maintaining the TGT TRK attitude. The 4-ft/s value was selected to minimize the amount of forward reaction control system (FRCS) propellant used. As a groundrule, if performing a burn axis by axis will result in greater than 2 ft/s being burned out of the FRCS, the burn should be replanned to be a +X RCS burn. Due to the Orbiter attitude at Ti, and based on the nominal burn ΔV 's, a multi-axis Ti execution can be estimated to be 50 percent FRCS and 50 percent ARCS. A 4-ft/s burn, therefore, would probably result in a 2-ft/s FRCS usage and is the upper limit for multi-axis execution.

4.1.35 Perform RR Auto Track Acquisition (Off-Nominal)

If the RR has not acquired the TGT by the time the range to the TGT has decreased to less than 60 kft, the crew attempts an acquisition using the AUTO track mode of RR operation. At approximately 60 kft, the probability of acquiring a TGT with a 0.5-square-meter radar cross section approaches 100 percent. The detailed AUTO track acquisition procedures are on the RNDZ OPS cue card and are explained in sections 3.3.4.6 and 4.3.2.

4.1.36 Target Ti Burn (Final)

Before targeting the final solution for the Ti burn, the crew transitions the GNC GPC's to OPS 202. As for the NCC burn, this is done to terminate sensor data processing into the FLTR SV so that burn solution comparisons are done based on nonchanging state data. If the Ti burn is to be executed using the OMS or the +X PRCS, the proper engine selection needs to be made on the MNVR EXEC display as well as the desired thrust vector roll (TVR) angle, Orbiter weight, and the engine gimbal trim angles. After being correctly loaded into the display, the data is then loaded (ITEM 22) into software in order to put the data onto the downlist for MCC visibility. On the REL NAV display the crew verifies that the source of SV data is correctly configured and then (if burn is +X) inhibits the incorporation of angle data into the NAV state. Since the GNC GPC's are already in OPS 202, this has no immediate effect. The inhibit is done to preclude the acceptance of inaccurate RR angle data into the filter immediately after the Ti burn is complete and the crew transitions back into OPS 201. The data would be inaccurate because the Orbiter will be maneuvered out of -Z axis TGT tracking attitude for the burn and RR gimbal angle measurement accuracies decrease as the antenna is pointed away from its -Z boresight.

The OMS/RCS PRPLT PAD should be checked at this point (sec. 4.3.4) and then periodically afterwards for the remainder of the rendezvous operations.

4.1.37 Solution Selection

The same rationale as in 4.1.27 (NCC) is used for this burn. The values of the comparison LIMITS are different since trajectory dispersions at Ti differ from those that can be expected at NCC.

4.1.38 Execute Ti Burn

The FDF block for this action is shown in figure 4-10. This is a mission-critical burn which sets up an intercept with the target. It is generally posigrade with some radial component. It is very time critical and cannot be slipped more than a few minutes.

Due to possible vehicle blockage of radar LOS to TGT, the Ku-band pointing mode is set to prevent the antenna from thrashing around in case of loss of track. If the burn is performed in LOMS (as is usual), vehicle angles should allow RR track to be maintained. Burns in ROMS, both OMS's, or +X RCS can result in RR break track. In that case, DAP B is used to get back to track attitude ASAP.

4.1.39 Ti As Multiaxis RCS Burn

See section 3.6.3 for discussion of this variation. A major driver for this decision may be a requirement for as much target tracking as possible. Propellant savings may also be a consideration.

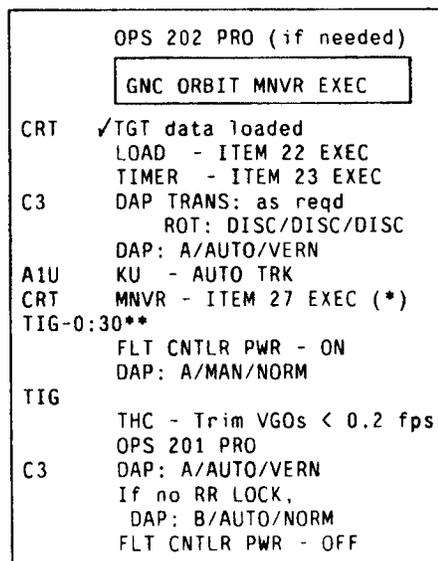


Figure 4-10.- Execute Ti burn.

4.1.40 Load/Execute Delay Burn (Off-Nominal)

Should a situation arise prior to execution of the Ti burn that requires a delay in the completion of the RNDZ, performing the RNDZ DELAY burn places the Orbiter in a safe trajectory relative to the TGT. This allows the crew and ground to assess the status of the problem and decide whether or not to continue with the RNDZ. See figure 4-11. Skip to section 4.1.47 for subsequent crew activity.

For short delays (one or two REV's), the ground will compute a phasing MNVR to return to the Ti position based on the most current onboard relative state, and will voice the MNVR target sets to the crew during the RNDZ sequence (see sec. 3.6.1.3). Desirable lighting conditions will be maintained as long as there is an integral number of REV's between the original and new Ti MNVR's. The crew has expressed an interest in remaining at least 6 n. mi. from the target when Ti is positioned at 8 n. mi.; the ground can easily accommodate this desire. Typically, a short delay will always be executed prior to a long delay.

A long delay (greater than two REV's) requires an opening rate to eliminate the need for the crew to continuously monitor the target. Long delays usually involve at least one crew sleep cycle. A 1-n. mi./orbit opening rate corresponds to a 0.3-ft/s MNVR assuming the current closing rate has been nulled. Typically, if propellant is available, the delay MNVR would be targeted to the point where the final phasing MNVR was executed (≈ 40 n. mi. trailing); this corresponds to an opening rate of 2.7 n. mi. per REV. Doing a larger than 1-n. mi./orbit opening rate MNVR reduces the probability of waking the crew to execute an additional opening rate MNVR. Also, the second RNDZ trajectory would be similar to the original trajectory.

Unfortunately, there is a propellant penalty for executing a Ti delay (see table 4-1). The magnitude of this penalty is dependent on the specific delay scenario. The table assumes a one-REV return to Ti.

TABLE 4-1.- PROPELLANT PENALTY

Scenario	Approximate penalty
1 or 2-REV delay	6 ft/s
24-hour delay Minimum phasing (23 n. mi.)	11 ft/s
24-hour delay Nominal phasing (40 n. mi.)	25 ft/s

In a loss of COMM case, the crew can target a rough Ti delay burn by targeting the T2 burn after NCC; this is supposed to be a burn which nulls Orbiter motion with respect to the TGT at Ti. This is not a verified procedure.

GNC 33 REL NAV	
CRT	INH Angles - ITEM 24 EXEC (*) OPS 202 PRO
GNC ORBIT MNVR EXEC	
	Load Eng Sel, TVR, WT and Trims per Ti Pad ✓TIG = Ti TIG Load Peg 7 TGTs per DELAY PAD, below Go to EXECUTE Ti BURN
ΔVX =	_____
ΔVY =	_____
ΔVZ =	_____

Figure 4-11.- Load delay burn.

4.1.41 RMS Operations

As discussed in section 3.3.5.5, the RMS wrist CCTV camera is a critical, close-in PROX OPS sensor. Also, problems with the RMS will impact plans for final approach (sec.3.9.2). The RMS cannot be deployed pre-Ti. This is because it could be an OMS burn and there would be too much stress on the brakes.

4.1.42 Target MC1 Burn (Preliminary)

The midcourse burns are targeted to intercept. Their BURN PADS are described in section 3.6.1.4 and they are burned axis by axis (sec. 3.6.3). The targeting terminology is:

$$T1 TIG = \text{BASETIME} + _ / _ : _ : _$$

MC1 (target set no.11) occurs about 8 minutes before sunset. Waiting until then allows most of the post-Ti REL NAV data to be incorporated into the MC1 computation while still being executed early enough to be propellant efficient. Also, orbital sunset minus 8 minutes leaves enough time between MC1 and MC2 for the manual out-of-plane (OOP) null.

Note: The MC burns may be done even with the tail-only RCS option, since tail-only mode is ignored by translations, so axis-by-axis translations can be done. If the intention is to make sure that all of the propellant comes out the aft RCS, however, the Orbiter must maneuver to +X burn attitude. This is not recommended for use.

Onboard solutions will be selected for all midcourse correction MNVR's. This is because the ground has no capability to improve the relative state information between the Orbiter and target for the midcourse correction MNVR computations. This is due to ground tracking uncertainties and the relatively close proximity of the two vehicles. Hence, the Orbiter solution for these MNVR's will always be selected.

In general, midcourse correction MNVR's, except MC2, will not be executed unless additional target sensor data has been obtained since the previous MNVR. This logic is subject to further analysis.

The rationale for this is as follows: Midcourse correction MNVR's are designed to correct the Orbiter intercept trajectory based on the most current relative state information. Since no additional relative state information is available, these MNVR's will only correct for trim errors or attitude maneuver effects. However, the onboard navigated state used to compute the MNVR could be in error by an amount as large as the computed MNVR. Hence, there is no real benefit to executing these MNVR's and they can be deleted to save propellant.

MC2 (sec. 4.1.51) is currently an exception to this rule. It is executed on an elevation angle to ensure the manual control trajectory is "standard." Also, MC2 must be targeted at least once so orbit targeting can automatically redefine its base time (MC2 TIG) for the MC3 and MC4 computations. Otherwise, the ground would have to supply the new base time and the crew would have to manually load it.

4.1.43 Verify Target Track Post-Ti

Before trying to configure for TGT acquisition, the crew verifies that the Orbiter is in proper TGT TRK attitude, usually -Z towards the TGT, and that the DAP is properly configured. The Ku system is placed back into its GPC mode so if a break-lock occurs on the TGT, the software will use GPC-supplied angle designates to automatically command a search pattern to reacquire the TGT.

Even though STRK angles are more accurate than radar angles, STRK marks are not preferred past Ti. The STRK's can define angles to a greater accuracy than the radar, but the accuracy decreases as the distance to the TGT decreases because the TGT is no longer a point source, and also because the angle data is not converted to the Orbiter c.g. frame. From Ti on in, the sensors are roughly equivalent, but the radar is more convenient to use. Also, of course, STRK is lighting-dependent, and optical tracking may be affected by target geometry and orientation.

If at this point it is known that the RR is inoperable, the crew attempts to use the STRK or COAS to collect REL NAV data on the TGT.

4.1.44 STRK Target Acquisition Post-Ti With Confirmed Radar System Failure

In the event of RR failure post-Ti, the crew is directed to a contingency block titled "STRK TARGET ACQ - RR FAIL." This contingency is described in detail in section 4.4.2, and is summarized as follows:

The hierarchy of sensor desirability is based on the accuracy of the resulting SV. The crew first attempts to perform a -Z STRK acquisition. This gives high accuracy while maintaining the -Z track attitude. This attitude

allows the crew to monitor the TGT in the COAS, and also eliminates the need for another attitude maneuver later in the profile to prepare for manual phase. Should the -Z STRK not be operable, however, the procedures call for the crew to give up TGT viewing and attitude continuity by attempting to acquire the TGT in the -Y STRK (as long as there is sufficient time to get to attitude before sunset). The -Z COAS is used only if no other sensors are functioning because the COAS data is less accurate than that of the STRK's, and because COAS data taking is a manual pointing operation resulting in higher fuel usage and fewer data points.

An IMU is deselected to stop IMU RM from changing the reference IMU during data taking (see sec. 3.9.4), and the DAP is verified to be configured for a 1° attitude deadband (DAP select A) and on the vernier control jets.

With the Orbiter operating on a 1° ATT DB and in a -Z target track attitude, the TGT should be within approximately 1° of the COAS centerline, assuming that the COAS misalignment with the body -Z axis is small. If the TGT is off COAS center by greater than 1°, it may be due to TGT SV inaccuracies in calculating the pointing direction toward the TGT. In this case, if the -Z STRK has not already acquired the TGT, it may be necessary to use the COAS to update the SV so that STRK has an initial pointing designate accurate enough to support TGT acquisition. With a valid -Z STRK acquisition the COAS data is not required. If COAS data is required, the crew takes marks on the TGT and incorporates data into the SV until the angular RESID's are less than 0.5°. At this point the SV pointing designate information should be accurate enough for the STRK to acquire the TGT in the 1° offset scan mode. The crew should then attempt to perform an STRK TGT acquisition instead of continuing to use up time and propellant pursuing further COAS data takes.

The following is a desperate last-ditch measure.

If only the -Y STRK is functional at this point (i.e., if the RR and the -Z STRK are known to be hard-fail permanently), the crew begins a rapid attitude maneuver to point the -Y STRK boresite at the predicted TGT position. For the maneuver, DAP select B and the primary RCS (NORM) are used to implement a rotational rate of 0.5 deg/s. After the maneuver is completed (approximately 3 minutes, unless the faster DAP B is selected), attitude control is reconfigured back to the vernier RCS to take advantage of the smaller ATT DB and vehicle rates possible when using these jets.

System configuration and data acceptance criteria are the same as for previous STRK data passes.

If after 5 minutes of attempted TGT acquisition the STRK still cannot lock on to the TGT, the crew is instructed to return to -Z target track attitude, if not already there, and begin taking COAS NAV marks. Five minutes allows the STRK to perform several 60-second field-of-view searches. With the short amount of time available for gathering optical data on the TGT, and with the upcoming trajectory correction maneuvers, it is important for the crew to take COAS marks often and for as long as possible to provide the best possible SV data. The best procedure is to take five marks early in

the pass and five marks late in the pass, and to take advantage of changing relative geometry.

4.1.45 SV Management

If valid RR track is established, the crew performs a FLTR TO PROP transfer to save the pre-Ti data (sec. 3.4.2.2), and then configures the RR angles back to the AUTO incorporation mode.

4.1.46 Off-Nominal Radar OPS

If the RR has not yet attained a TGT lock-on, but is not known to be failed, the crew attempts to acquire a lock-on by utilizing the AUTO TRACK mode of operation (see "cue cards" in sec. 3.3.4.6). If there is still no acquisition, the crew assumes that the Orbiter-to-TGT range may be the reason. The Orbiter is maintained in the -Z-to-TGT attitude in hopes that the RR will lock on as the Orbiter approaches the TGT. The crew inhibits range, range rate, and angle data acceptance into the NAV filter. If the -Z STRK is functioning, the crew performs an STRK acquisition. Otherwise they perform COAS data takes. If at any time during the STRK or COAS data taking should the RR acquire the TGT, the NAV inputs are reconfigured to use the RR data because of the increased SV accuracy obtained through the use of range and range rate data.

4.1.47 If Delay Burn Was Performed (Off-Nominal)

If Ti Delay has been performed, a number of activities will occupy this extra 90 minutes.

First, retargeting Ti with the new base time received from the MCC will restart the counter. As a first approximation, add 90 minutes to the old base time.

Second, since the TIG is near orbital noon, an STRK pass can begin soon afterwards. Take STRK marks until near sunset; continue to take RR marks.

Essentially, the checklist is reentered at Ti TIG -1:30 (without doing NCC again!). Another STRK pass is performed (see sec. 4.1.20), and Ti is approached again. If there is good RR tracking, the MCC may advise the crew to not perform the STRK pass.

4.1.48 Target MC1 Burn (Intermediate/Final)

With the advantage of an SV improved by post-Ti tracking, the MC1 burn is targeted twice more.

4.1.49 Execute MC1 Burn

Except in highly unusual circumstances (e.g., badly executed Ti burn), this will be a small axis-by-axis RCS burn. It is possible that the burn TGT's will be less than the desired trim limits; in that case there is no need to execute the burn.

An explanation of the direction of midcourse burns is found in section 2.8.7.

4.1.50 End STRK Navigation for Post-Ti Data Pass (Off-Nominal)

This procedure is utilized if the STRK is used to gather target data post-Ti due to a failed RR, or if STRK angle data is desired over RR data.

At sunset, the angle input to NAV is inhibited so that erroneous STRK data is not incorporated should the STRK lock onto another light source. Since the only possible sensor data for the remainder of the RNDZ is radar data, the software is set up to accept RR angles should they become available.

The STRK's are placed in their TERM/IDLE mode and the shutter doors are confirmed to not be latched open.

At the end of each STRK pass, the IMU's are reselected to configure back to the three-LRU level.

If radar data becomes available as the Orbiter closes on the TGT, the crew is instructed to monitor and accept the data, using criteria laid out in the RR NAVIGATION block (see 4.1.30, 4.1.31, 4.1.32).

4.1.51 Target MC2 (Preliminary/Intermediate)

The second midcourse burn differs from others in that the TIG is tied to an Orbiter-target LOS elevation angle rather than a preset clock time. The preliminary targeting block is shown in figure 4-12.

```

CRT    ✓  SV SEL correct
        GNC 34 ORBIT TGT
        TGT NO - ITEM 1 + 1 2 EXEC
        ✓  TGT Set data:
           T1 TIG = BASE TIME +0/00:47:00
           EL  +26.6
           ΔT  +33.1
           ΔX  +0
           ΔY  +0
           ΔZ  +0
           Note Nominal T1 TIG in pad
           COMPUTE T1 - ITEM 27 EXEC

           Note solution in pad and inform MCC
  
```

Figure 4-12.- Target MC2 (preliminary solution).

The use of an elevation angle as a cue for MNVR execute forces a standardized final approach profile to the TGT and maintains lighting conditions. Such a profile has a known LOS rate regardless of the range dispersions prior to MC2. It involves essentially zero inertial line-of-sight rates during the crucial final minutes of the approach. This allows straightforward, out-the-window monitoring to give crewmembers cues for any off-nominal trajectory and to define direct "fly-to" corrective MNVR's. This burn shapes the intercept to occur in 125° (32 minutes) of orbit travel. It is cued to occur when the elevation angle of the TGT is about 28° . This occurs near orbital midnight.

In general, if the T_i point was long, then MC2 will be delayed, and if the T_i point was short, MC2 will be early. Flight experience has been that T_i tends to be long (late MC2 also equals early orbital sunrise relative to manual takeover).

Note: The terms "long" and "short" as applied to T_i (and any other RNDZ MNVR locations) refer explicitly to range from TGT, not to range from previous MNVR point. Thus, T_i is "long" if the TIG location is farther than expected from the TGT; however, from the point of view of earlier burns, the same result could be viewed as having fallen "short" of the aim point, as in artillery terminology. To avoid ambiguity, always refer "long" and "short" to the range-to-TGT, not range-from-starting-point. See figure 4-13.

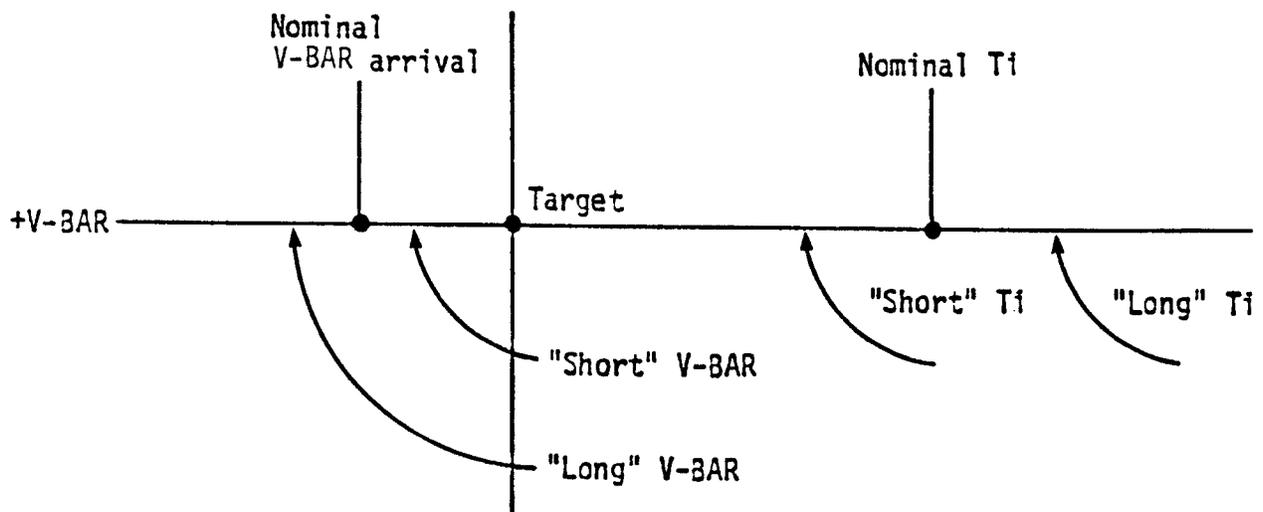


Figure 4-13.- Long/short terminology.

At some point, lighting can no longer be sacrificed to maintain a "standard" manual control trajectory. That limit was chosen to be minus 3 ("early") to plus 7 ("late") minutes from the nominal TIG. This will maintain sunrise between MC3 and MC4 and ensure a lighted manual control initiation at MC4 plus 2 minutes.

See section 4.1.42 for a discussion of rationale for sensor fail MC2 targeting.

See section 3.5.5.3 for discussion of possible ORB TGT alarm "TGT EL ANG."

Acquisition of additional tracking data may result in significant changes to the MC2 TIG (several minutes) for the intermediate targeting. Each new TIG should be read down to the MCC since the solutions are not downlisted.

4.1.52 Execute RNDZ Breakout If No Sensor Data Or If No Filter Convergence (Off-Nominal)

See section 4.6 for discussion. The OMS/RCS PRPLT PAD (sec. 4.3.4) may also be the cause of a BREAKOUT call near this point.

4.1.53 CCTV Configuration

If required, power up CCTV and VTR per cue card, set SCAN to UNDERSCAN, perform PAN/TILT RESET, and load new tapes in VTR's.

4.1.54 Perform Manual Out-of-Plane Null

This manually-executed axis-by-axis RCS burn (fig. 4-14) is performed based on cues from SPEC 33, REL NAV. Ti had set up a 180° transfer from this point to intercept. Careful monitoring of the Y and Y-DOT parameters on REL NAV is called for. Although Ti is supposed to create a node (Orbiter/target in-plane crossing) half a REV prior to intercept (see sec. 3.5.7), the actual time the node occurs can vary by up to 10 minutes due to NAV updates. When executed using Y thrusters, the burn drives Y-DOT to zero, so Y should not increase substantially afterwards.

If the burn is missed, the Y-DOT component should be nulled ASAP and the rest of the planar difference will have to be taken out manually during terminal phase. While this complicates that operation, it is certainly doable. See section 2.4.2.2 for a theoretical discussion of the orbital dynamics effects.

Flight experience has shown that the Ti burn is often successful in nulling out-of-plane rates to the point that the subsequent manual burn is not required. Generally the Y-DOT is a couple tenths of a foot per second.

```

GNC 33 REL NAV
CRT      When Y = 0
F7      FLT CNTLR PWR - ON
C3      DAP:A/AUTO/NORM
        DAP TRANS: as reqd
        THC - null YDOT

        If -Z-AXIS TRACK,
          +YDOT = FWD THC left
                AFT THC right
        If -Y S TRK TRACK,
          +YDOT = FWD THC down
                AFT THC out

        DAP:A/AUTO/VERN
F7      FLT CNTLR PWR - OFF

```

Figure 4-14.- Manual out-of-plane null.

4.1.55 Target MC2 Burn (Final)

Once the last MC2 solution is computed (fig. 4-15), its TIG is compared to the preflight TIG, and the "TIG slip" is noted. Note that the "slip" can be in either direction, either ahead ("later") or back ("earlier").

```

✓ SV SEL correct
GNC 34 ORBIT TGT
CRT      TGT NO - ITEM 1 +1 2 EXEC
        COMPUTE T1 - ITEM 27 EXEC
✓ TIG change between -3 and +7 min

.....If TIG Change <-3 OR >+7 min.....
.
.   Set BASE TIME to (Nominal MC2 TIG -3,+7 min)
.   as appropriate.
.   Load - ITEM 26 EXEC
.   TGT NO - ITEM 1 +1 9 EXEC
.   ✓ TGT Set data
.   T1 TIG = (BASE TIME)
.   EL      +0
.   ΔT     +33.1
.   ΔX     +0
.   ΔY     +0
.   ΔZ     +0
.   COMPUTE T1 - ITEM 27 EXEC
.
.....
Set EVENT TIMER counting to MC 2 TIG
Note solution and inform MCC

```

Figure 4-15.- Target MC2 (final solution).

A different TGT set (one based on time rather than elevation) is called up when TIG slips more than -3 or +7 minutes. The reason MC2 must be done within a particular time interval is that this burn will determine the lighting for the manual phase. A TIG slip greater than -3 or +7 minutes causes unacceptable orbital lighting conditions during manual terminal phase. (Sunrise must occur by MC4.) Changing BASE TIME prior to calling up the new target set allows the new BASE TIME to be changed by FSW in all sets. This saves keystrokes and simplifies crew procedures.

The reason for the new set is procedural. The new TGT set number is a quick indicator in the MCC that MC2 is being done on time rather than elevation angle. This is to avoid any possible confusion by seeing the old TGT set number selected.

4.1.56 Perform MC2

The burn is executed like any other axis-by-axis burn.

4.1.57 If in -Y STRK Track ATT, Return to -Z Axis Target Track (Off-Nominal)

If the -Y STRK had been used post-Ti, the Orbiter will still be in the -Y STRK TGT TRK attitude. In order to support the manual phase operations, it is necessary for the Orbiter to be aligned with its -Z axis pointing toward the TGT. The maneuver to the -Z axis TGT TRK attitude is delayed until after MC2 so that the approximately 8-minute-long attitude maneuver does not interfere with the execution of the OOP null or MC2. If the actual execution time of the OOP null and MC2 are such that it could be accomplished earlier, the crew has the option to execute the maneuver anytime after sunset.

4.1.58 Timeline Notes for No Radar Final Phase (Off-Nominal)

In the case of a failed RR, the crew will take over manual control of the trajectory at the earliest possible moment. This is done to keep the trajectory dispersions small in the manual phase.

The crew begins manual translational control at sunrise, based on out-of-the-window observation of the TGT.

A detailed discussion of this contingency is found in section 4.4.2.

4.1.59 Target and Perform MC3 Burn

This burn is scheduled to occur exactly 10 minutes after MC2. This has no significance other than correcting the trajectory so dispersions do not accumulate. It may be small enough to be skipped.

4.1.60 Target and Perform MC4 Burn

This burn is scheduled to occur exactly 10 minutes after MC3. Nominally, this is 3 minutes after orbital sunrise, and it is always expected to occur soon after sunrise in any dispersed cases. It may be small enough to be skipped. It will not be executed unless additional target sensor data has been obtained since the previous MNVR.

4.1.61 Establish Inertial Line-of-Sight Rates

Manual control is initiated 2 minutes after MC4.

The RNDZ profile has been designed to set up this situation, which was chosen in the first place because it creates an easy "fly-to" environment where course dispersions are quickly obvious to the crew and where the required corrections are equally straightforward. See figure 4-16 for the procedures block. The COAS is centered onto the TGT by RHC commands, and the Orbiter is placed in inertial hold.

```

A6U  ✓DAP ROT:  DISC/DISC/DISC
      TRANS:  PULSE/PULSE/PULSE
      ✓SENSE - - Z
      FLT CNTRLR PWR - ON

MC2   +22:00 **
      DAP:  A/MAN/NORM
      THC - ±X as reqd until
      EL LOS rate = 0 mrad/sec
      (TARGET stationary in COAS)
      ✓ADI ATT - LVLH
      RHC as reqd until Yaw = 0
      DAP:  A/MAN VERN,  NORM as reqd

      GNC UNIV PTG

CRT   DAP ERR - ITEM 24 EXEC (*)

```

Figure 4-16.- Establish inertial LOS rates.

DAP ERR is selected to provide insights into reasons for small LOS dispersions (since they may initiate THC inputs) and to allow anticipation of deadbanding effects of LOS rates.

A wait until MC2 plus 22 minutes before going to inertial attitude hold in the manual phase is chosen because nominally 22 minutes after MC2 the inertial LOS rates to the TGT go to zero. This time depends upon the elevation angle and the transfer time, but is independent of the range at MC2. Inertial attitude hold starts at exactly MC2 plus 22 minutes, rather than when the radar actually shows a zero inertial LOS rate, because the radar LOS data has not been dependable for LOS rates. For a no-radar case, inertial attitude hold will be initiated at sunrise (see sec. 4.4.2).

On a long dispersed case (+3 sigma) during the manual phase, sunrise can occur early or late, depending on what happened to put the Orbiter on the long trajectory. Basically, if the Orbiter starts out from Ti closer than nominal, it will end up a lot closer to the TGT at sunrise than if it started from further away. When NAV thinks the Orbiter is further away from the TGT at Ti than it actually is, targeting will be correcting for its perceived position and may end up sending the Orbiter too long. The same is true for a short case. Sunrise could occur earlier or later depending on where the Orbiter actually is and where NAV thinks it is when it hits the Ti point.

Normally, the crew must make -X pulses to maintain the TGT in the COAS at manual takeover. The inertial LOS rate was positive and decreasing since Ti, and nominally passes through zero at manual takeover, and would go negative if no -X pulses were made.

4.1.62 Reconfigure RR

At a range of 800 feet, it is assumed that the Orbiter is under manual trajectory control and relative rates are small. Certain specific actions in preparation for V-BAR arrival can now be taken (fig. 4-17).

The RR system is configured to its low power state. During normal operations, the RR automatically steps down its transmit power as the range to the TGT decreases. Power output steps down by 12 dB when range decreases to less than 2 miles (MED power), and steps down another 12 dB when range becomes less than 1.1 mile (LOW power). At 800 feet, therefore, the radar will have downmoded automatically to the LOW power output. Should a breaklock occur, however, the RR would automatically begin a search for the TGT and would search at the maximum power setting as designated by the KU RADAR OUTPUT switch on panel A1U. By placing this switch in LOW setting, the crew ensures that the payload being approached will not be subjected to the full output power of the RR at the close ranges. See section 3.3.4.7 for the theoretical background behind this action.

Moding to TOT ERR is a crew call; it helps show arrival at the V-BAR.

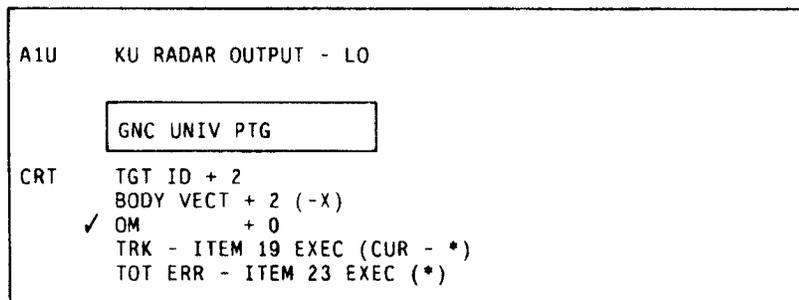


Figure 4-17.- Configure for V-BAR.

4.1.63 Configure UP for V-BAR

In preparation for V-BAR arrival, some new attitude control laws are present (fig. 4-17). The UNIV PTG software is configured to support attitude control while on the TGT V-BAR, even though the Orbiter has not reached the V-BAR yet, and the DAP is in manual attitude control. Attaining a stable position in front of the TGT on its V-BAR is a combined effort of DAP assisted attitude control and manual translational stationkeeping. When the Orbiter reaches the TGT V-BAR, it is oriented with its -X axis pointed toward the center of the Earth and its +Z axis pointed in the direction of orbital motion. Note: Changing pointing vector will change theta by 90°!

Time to V-BAR (in minutes) can be determined by noting the angle yet to be traversed, and dividing by 4 degrees per minute. Multiplying this interval (converted to seconds) by the observed R-DOT gives the distance to be covered before V-BAR arrival. Subtracting that distance from the current range gives a useful approximation of where on the V-BAR the Orbiter will arrive. As arrival time approaches, this approximation will get better and better.

4.1.64 Follow Range Braking Gates

As the Orbiter approaches the TGT, the closing rate is gradually decreased until finally the TGT is in close enough proximity for capture with the RMS. The tradeoff in the braking gate schedule (fig. 4-18) is that if the closing rate is too low, the approach takes a long time (and the Orbiter will not get close enough by sunset). A large closing rate results in a large velocity null MNVR, when in close proximity to the TGT. The braking gates selected allow for plenty of closing velocity to accomplish an approach to the TGT without significant plume impingement.

RNG	R-DOT
2000'	-4.0
1500'	-2.0
1000'	-1.0
500'	-0.5
400'	-0.4
300'	-0.3

Figure 4-18.- Braking gates.

4.1.65 If Range = 200 Feet Before Reaching V-Bar (Off-Nominal)

The baseline transition and PROX OPS trajectory results in the Orbiter's arriving at the V-BAR while still outside of the 200-foot range to the TGT. If, however, the approach was made at higher closing rates (a "hotter" approach, or "short" case), the Orbiter may reach 200 feet before having acquired the V-BAR (fig. 4-19). In this case, the crew is instructed to null out the remaining closing rate and continue the transition to the V-BAR while at 200 feet distance from the TGT (fig. 4-20). To reduce the contamination and torque effects of the Orbiter RCS plumes, the "LOW Z" DAP mode is selected prior to performing any of the braking MNVR's, and then is immediately exited for subsequent LOS control.

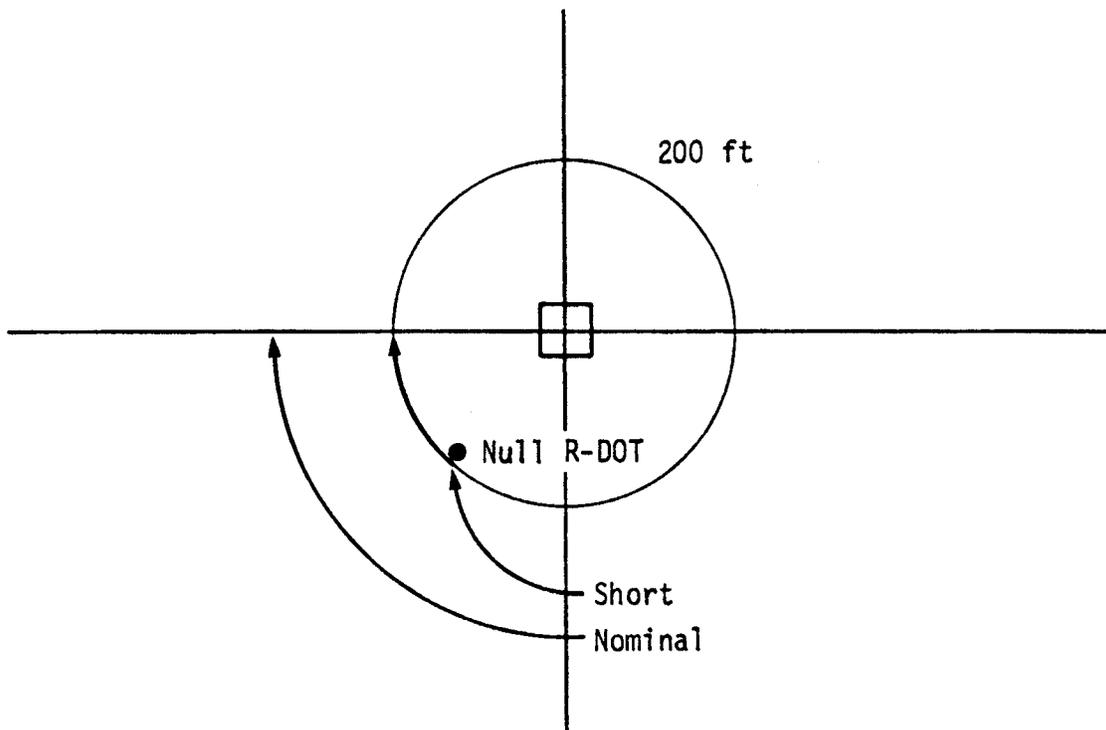


Figure 4-19.- "Hot" approach("short" case).

4.1.66 Configure DAP for Proximity Operations

The loaded DAP CONFIG's are configured with the appropriate values for PROX OPS usage. There are three parameters that are changed from the RNDZ configuration. The translational pulse sizes for both DAP's A and B are reduced to 0.05 and 0.01 ft/s, respectively. This gives the crew finer control over the Orbiter trajectory during the close-in operations leading to TGT grapple. A value of 0.01 ft/s is the smallest legal value for entry into software and ensures that the minimum possible jet-firing duration is executed whenever the crew commands a translational pulse in DAP B.

The DAP B DISC ROT NORM is changed to 0.2 deg/s making it consistent with the DISC ROT values loaded in the other three DISC ROT positions. For nominal operations this change will have no effect. Should the need arise to perform a TGT flyaround to support capture activities however, it is important that the flyaround maneuver proceeds at a constant ROT rate, no matter how the crew configures the DAP SELECT. To support this, the value for the DISC ROT must be the same in both DAP's and for both RCS JET selections.

```

A6U   DAP:  A/MAN/NORM
      DAP TRANS: PULSE/PULSE/PULSE, LOW Z
      THC - as reqd to null R-DOT
      When R-DOT stable at 0,
      DAP TRANS: PULSE/PULSE/PULSE, NO LOW Z
      Maintain target stationary in upper half of COAS
      DAP:  A/MAN/VERN, NORM as reqd

```

Figure 4-20.- Transition to V-BAR.

4.1.67 Establish V-BAR

Once the Orbiter is in exact tail-to-Earth attitude while the TGT is also along its -Z LOS, it has arrived at the V-BAR (this can be observed on the ADI and, more precisely, on the UP TOT ERR values). The UP control mode loaded earlier is activated by going DAP AUTO (see fig. 4-21), and any motion above the V-BAR is nulled. Since the c.m. of the Orbiter is substantially below (along the R-BAR, in this tail-to-Earth attitude) the crew compartment (about 40 feet, in fact), the LOS to a TGT whose c.m. is at that same altitude will be noticeably depressed (see PROX OPS Cue Card, section 4.3.6, for typical angles).

```

CRT   ✓UNIV PTG TOT ERR - small
A6U   DAP:  A/AUTO/NORM

      THC - -X(down) as reqd ( -0.1 fps/100 FT R)
      THC - -Z(in) as reqd to ensure proper closing rate
            per PROX OPS cue card
      Maintain target in lower half of COAS, R-DOT ≤ 0
      DAP:  B/AUTO/VERN, NORM as reqd

```

Figure 4-21.- Establish V-BAR.

4.1.68 Adjust Closing Rate as Required

This procedure is shown in figure 4-22.

The approach rate along the V-BAR should be maintained at about 0.2 ft/s (or other specified rate, per checklist; a rule of thumb for approach rate is to use range in kft for the ft/s R-DOT). The approach path should keep the TGT above the PLB for RCS plume impingement reasons as well as orbital dynamics considerations (also, most payloads are grappled over the PLB for payloads deployment and retrieval system (PDRS) reasons). Once within 200 feet, low Z mode should be selected; however, if flown smoothly, there will be little need for much expensive thrusting in this mode.

A6U	DAP: A/AUTO/NORM
	DAP TRANS: PULSE/PULSE/PULSE, LOW Z
	THC - --Z until R-DOT = -0.2 FPS
	DAP: B/AUTO/VERN, NORM as reqd
	Maintain target over PL Bay

Figure 4-22.- Adjust closing rate.

4.1.69 Configure Ku-Band System for Communications

Within about 80 ft, the RR will break track and is no longer usable. In configuring back to the standard on-orbit mode where the Ku system is used for communications, the KU ANT ENA is disabled on REL NAV so that the Ku system once again receives pointing designates from the SM computer for the TDRS. The Ku system switches are set to their standard on-orbit positions. Timing is a crew call.

4.1.70 Inside 60 feet, Deselect Low Z DAP Mode

The plume field from the PRCS is such that a relatively "quiet" zone exists over the PLB even when configured without the low Z mode active. When the TGT positioning is such that the TGT is in this "quiet" zone, the Orbiter DAP no longer needs to be configured to the low Z mode. The standard capture position for payloads by the RMS is over the center of the PLB, and so as can be seen in Figure 3-9, at a range of approximately 60 feet the TGT is "safe" from the major effects of the PRCS plumes (unless it is very large and overhangs the Orbiter nose). Braking burns can now be performed economically.

4.1.71 Null Rates to Perform Target Capture

When the Orbiter has approached to a close enough range that the RMS can effectively capture the TGT, the remaining relative rates are nulled by the crew. One of the clearest cues from the crew's perspective to quantify relative rates and assist in the final velocity nulling before capture, is the view from the RMS EE camera. As was discussed in 4.1.41, the EE camera is oriented such that the view is directly along the Orbiter +Y axis with the top of the view being away from the Orbiter PLB. Motion of the TGT up or down in the camera FOV is therefore an indication of relative closing or opening rate. Motion left or right in the FOV indicates TGT motion forward or aft (respectively) in the PLB. Since at these close-in ranges the RR does not function, the EE camera view is very helpful to accurately position the TGT and null out translational velocities.

4.1.72 Perform Flyaround of Target (Off-Nominal)

See section 5.2 for discussion of these PROX OPS techniques.

4.1.73 Capture Target With RMS

Once the TGT is physically attached to the Orbiter, immediate rendezvous/ PROX OPS concerns are over. However, contingency or inadvertent release always remains a possibility.

4.1.74 Disable Rendezvous Navigation

Orbiter software configuration can now be returned to normal on-orbit mode (fig. 4-23). The STRK's are returned to STRK mode (sec. 3.3.2). To tidy things up, all NAV mark data is inhibited. Ku pointing data is returned to TDRS mode. RNDZ NAV is disabled (in the CONTINGENCY RNDZ book, this is an MCC call).

```

A6U  ✓FLT CNTLR PWR - OFF
      GNC 22 S TRK/COAS CNTL
CRT  -Z (-Y) S TRK ITEM 4 (3) EXEC (*)
      GNC 33 REL NAV
      INHIBIT  RNG          - ITEM 18 EXEC (*)
              R-DOT        - ITEM 21 EXEC (*)
              ANGLES        - ITEM 24 EXEC (*)
      ✓KU ANT ENA          - ITEM 2 EXEC (no *)
      RNDZ NAV ENA        - ITEM 1 EXEC (no *)
  
```

Figure 4-23.- Disable rendezvous NAV.

4.2 RENDEZVOUS VARIATIONS

The preceding section of the book dealt with the rationale for RNDZ MNVR's of a flight plan based on the STS 51-L Spartan rendezvous. There are other types of RNDZ missions which will differ procedurally from the standard 51-L sequence, usually due to some essential differences in starting points. The following paragraphs discuss these variations.

4.2.1 Delayed Rendezvous

Both Orbiter and TGT systems reasons may induce a significant delay into the planned RNDZ, beyond that delay possible by performing the "Ti Delay" burn (see sec. 4.1). In general, "Rendezvous OPS Delays" push off the final arrival at the target. Such delays can be pre-Ti "Rendezvous Delay" MNVR's, or at Ti ("Ti Delay"), or even post-Ti (V-BAR stationkeeping).

4.2.1.1 Several Hours Delays

For delays prior to Ti, if convenient, the nominal MNVR's will be adjusted to slow phasing so that the Orbiter arrives at the Ti point at the desired delay time. This is referred to as "Rendezvous Delay." Otherwise, the nominal RNDZ plan will be executed until Ti, where a delay will be done; this is the classic "Ti Delay."

The most convenient way to delay a RNDZ is to slow the catchup rate such that the Orbiter makes a RNDZ with the TGT at the desired time. This can be done at any preplanned phasing MNVR (NC), typically with no propellant penalty, or an additional MNVR can be inserted into the RNDZ profile. Mission activities and propellant budgets will determine which option to use.

If it becomes inconvenient to slow the phasing prior to Ti, continue the nominal RNDZ profile and delay at Ti. Up until Ti, the Orbiter is not flying an intercept trajectory. Hence, Ti is the last point at which the RNDZ can be delayed. Additionally, Ti is a well defined point relative to the TGT, since onboard relative navigation systems are within acquisition range, and a delay MNVR is easily computed.

4.2.1.2 24-Hour Delays

Prior to the actual day of RNDZ, NAV sensors are not required since the ground is targeting all MNVR's and the separation of the Orbiter and the TGT is sufficiently large. One potential motivation for a 24-hour delay is a sensor failure with hope of repair through IFM or workarounds. Most of the load for a 1-day delayed RNDZ falls on the MCC planning shift, which must update the trajectory column on the RNDZ timeline page. Every effort will be made to make the delay transparent to on-orbit operations.

4.2.2 Preplanned Optional Return

Some missions (e.g., Hubble Space Telescope) provide a preplanned opportunity after deployment and separation for return, either for inspection, repair, or retrieval. Propellant status and consumption are the greatest concerns in this operation, and since the requirements are assessed premission as in a typical RNDZ, good margins can be assumed. However, violation of propellant redlines is still most likely to be the cause for a breakout call, if one occurs.

4.2.3 Contingency (Unplanned) Rendezvous

Ever since STS 51-D needed to rendezvous with the deployed Syncom F-3, and a checklist was sent up over the teleprinter, it has been standard to carry a Contingency Rendezvous book as part of the FDF. The major constraint is propellant, which is not held back in preflight planning and earlier on the actual flight, to support this contingency; due to consequent propellant budget problems, the MCC planning shift activities will be intense. The major driver for the actual RNDZ will be the experience and training level of the individual crewmembers; for RNDZ and PROX OPS, this unpredictable factor will most heavily influence the amount of air to ground (A/G) discussion during actual operations. The PROX OPS phase of such a mission will be the most unpredictable and trickiest. It will probably require real-time SES runs and attitude/ pointing calculations.

The following assumptions and guidelines were used in generating the Contingency Rendezvous book, which is carried on all missions not involving a planned rendezvous.

- a. Standard rendezvous procedures are included for a Spartan-type profile up to and including V-BAR arrival, with two star tracker passes prior to T_i .
- b. PROX OPS procedures are provided for a V-BAR approach to 200 feet, followed by stationkeeping, flyaround, and/or approach to an LVLH or inertially stabilized payload. The appropriate path through the options presented will be determined as early as possible when the requirement for the rendezvous is established.
- c. The timeline assumes a 190 n. mi. circular orbit. Day/night assumes a 16° beta. The rendezvous will be planned such that the timeline will be accurate at $PET = 0$. Orbital period increases by about 1 minute for every 27 n. mi. of additional orbital altitude. Therefore, at 217 n. mi., T_i would occur 1 minute later than shown.
- d. Targeting I-loads will be selected preflight from sets of I-loads for orbits between 130 n. mi. and 310 n. mi., in increments of 20 n. mi. Data for all sets is presented in the book for reference.

- e. All burns are planned to be RCS. An OMS burn procedure for rendezvous is included in the event that a larger burn is required.
- f. NORM Z is used throughout the PROX OPS except for an approach from 200 feet to 60 feet, where LOW Z is used. When the target is over the payload bay within 60 feet, use of NORM Z will be resumed.
- g. Ranging rulers and subtended angle charts are provided for payloads ranging in size from 2 to 50 feet. Actual payload size will result in a range bias of up to 10 percent.
- h. Contingency procedures are included to cover radar fail, loss of VRCS, and RNDZ NAV safing and recovery.

4.2.4 Ground-Up Rendezvous

A key point to remember here is that for a ground-up RNDZ, the first RNDZ burn is ascent. All subsequent burns also affect the final profile. If any burn deviations occur, immediate replanning must be initiated. In every case flown so far, one or more satellite deploys have preceded the RNDZ, so even those MNVR's must be made with subsequent RNDZ impacts in mind. See appendix A, discussions of STS 41-C (first RNDZ), STS 51-A (first RNDZ), STS 51-I.

4.2.5 Multiple Rendezvous

Propellant consumption is the biggest concern in this variation, particularly the forward RCS. Radar fail cases are especially bad. A secondary concern is in procedures design, in that both RNDZ sequences should be built to look as alike as possible (this minimizes RNDZ-specific training requirements). Payload thermal constraints between recoveries may require -Y STRK operations (there are also beta angle considerations here). See appendix A, discussion of STS 51-A.

4.2.6 Rendezvous From Above

While not yet performed or scheduled, this kind of RNDZ was actually among the earliest types of STS RNDZ profiles planned (originally, LDEF was planned to be deployed above SMM, and then SMM would be retrieved: LDEF would be retrieved after STRK was deployed above it). The profile was abandoned due to multiple payload performance requirement, rather than MNVR design requirements. The leading rendezvous techniques issue was sensor performance when the look angle is below local Orbiter horizontal and lighting constraints, since the approach will be from above and ahead rather than from below and behind. Every effort will be made to keep the nominal procedures of NC3 to Ti to terminal phase as close to "standard" as possible.

4.2.7 Maneuverable Target

This future option is discussed in detail in section 8.1 (along with STS standard retrieval policy relevant to maneuvering TGT's), and it is likely to be a fairly common one. The TGT orbital adjustments must be completed prior to the first STRK pass of the Orbiter or major dispersions will result (possibly large enough to call a breakout). There may be a tradeoff between STRK and manual phase visibility. Some of these considerations were involved with planning for STS 51-A, since both payloads did lower themselves into the retrieval orbit, although this was completed prior to STS launch.

4.2.8 Elliptical TGT Orbit

Analysis has revealed concerns in terminal phase radar-fail cases; inertial LOS rates cannot be guaranteed. Lack of anticipated requirements has forestalled any further investigation of this option, but experience on STS 51-I (see appendix A) suggests there may be procedural impacts.

4.3 RENDEZVOUS CUE CARDS

Standardized procedures, which can be used at several points in the RNDZ phase, are defined on cue cards. All RNDZ cue cards are listed below. Since many are used on a standard RNDZ profile and involve many different specialized systems and procedures, they are discussed here. Specialized cards are discussed in related, specialized sections elsewhere in this book.

4.3.1 Execute RCS Burn Cue Card

This RCS procedure is shown and discussed in section 6.2.5, "Special Burns." The cue card is called out in PERFORM NC BURN (4.1.9), PERFORM NH BURN (4.1.17), EXECUTE NCC (4.1.28), PERFORM MC1 (4.1.49), PERFORM MC2 (4.1.56), PERFORM MC3 (4.1.58), and PERFORM MC4 (4.1.60).

4.3.2 RR Auto Track ACQ Cue Card

This procedure is used if GPC mode acquisition is unsuccessful (perhaps the SV is not good enough to guide the antenna close enough to the TGT). It is shown and discussed in section 3.3.4.6. The cue card is called out (if no lock on) at R = 60 kft (sec. 4.1.30), and again post-Ti in VERIFY TARGET TRACK (4.1.43).

4.3.3 COAS Navigation Cue Card

The general principles for the use of COAS in taking NAV marks are discussed in section 3.3.3.3; specific CRT keystrokes and switch throws are defined on this cue card (fig. 4-25). COAS NAV is a multiple-failure off-nominal

situation. The "FORCE" option is used rather than "AUTO" so that the crewmember can decide post-mark whether it was a good one or not, before entering it into REL NAV.

The optimum rate is not to exceed two marks per minute. More than three marks provides little improvement in SV, while costing propellant. See discussion of rationale in section 4.1.14. The mark must be less than 2 minutes old when forced, or it will be rejected by the filter.

The FLTR TO PROP is called for assuming the existing FLTR SV is better than the PROP SV; if COAS NAV is called out for some other reason, this action may not be desirable, so consult MCC.

The cue card is called out post-Ti in VERIFY TARGET TRACK (4.1.43) and twice in S TRK TARGET ACQ-RR FAIL (sec. 4.1.44).

GNC 22 S TRK/COAS CNTL	
COAS:	SIGHT MODE - ITEM 22 EXEC REQD ID - ITEM 21 +1 EXEC
GNC 33 REL NAV	
INH Angles - ITEM 24 EXEC (*)	
If tgt in COAS FOV,	
FLTR TO PROP - ITEM 8 EXEC	
COAS - ITEM 14 EXEC (*)	
FLT CNTLR PWR - ON	
DAP ROT: PULSE/PULSE/PULSE	
DAP: as reqd	
Center target in COAS	
ATT REF pb - push	
If mark acceptable,	
FORCE Angles - ITEM 25 EXEC	
Repeat COAS marks as reqd	
When COAS marks complete,	
DAP: A/AUTO/VERN	
DAP ROT: DISC/DISC/DISC	
FLT CNTLR PWR - OFF	

Figure 4-25.- COAS navigation cue card.

After taking COAS mark, it could be up to 8 seconds before RESID and RATIO values are displayed. These values will continue to be recomputed until the mark is accepted or a new mark is taken, so these displayed values may change slightly every 8 seconds. After performing FORCE, it could then be up to 8 seconds more before SV UPDATE values appear. Note that these values will subsequently remain on display for only another 8 seconds and then return to zero.

4.3.4 Rendezvous OMS/RCS PRPLT PAD

This PAD is discussed in detail in the OMS/RCS Quantities section, 3.8.4.1. The crew should begin paying serious attention to this PAD prior to T_i (see section 4.1.36).

4.3.5 RNDZ OMS Burn

See section 6.2.5.1 for this procedure and rationale. The cue card is called out as an option in PERFORM NC BURN (4.1.9), EXECUTE NCC (4.1.28), and EXECUTE T_i (4.1.38).

4.3.6 PROX OPS Cue Card

The PROX OPS cue card (fig. 4-26) contains four columns of data keyed to Orbiter-target range. These columns greatly facilitate PROX OPS. The cue card is called out in ESTABLISH V-BAR (4.1.67) and used thereafter until grapple or separation.

4.3.6.1 RR/COAS Angle

Due to the large angle dimensions of the Orbiter, and the consequent position of some sensors high above the Orbiter c.m. on the V-BAR, their LOS to the target is depressed (fig. 4-27). This vertical separation is large enough to induce observable orbital mechanics forces, if this trigonometric effect is overlooked. Column 1 on the cue card presents the values for RR and for COAS POSITION that, if followed for the given range, will put the Orbiter c.m. precisely on the TGT V-BAR.

4.3.6.2 FWD CCTV POSITION

The same trigonometric considerations hold for the PLB A and D CCTV's. They are assigned their own column because their tilt sense is different from the RR and COAS. The CCTV's are about 4 feet farther aft than the COAS and RR.

RANGE	RR EL/COAS Position	FWD CCTV POSITION	FLY AROUND VELOCITY	VBAR APPROACH RATE
200	-12.9°	78.2°	.2 FPS	-.2 FPS
250	-10.3°	80.5°	.25 FPS	
300	-8.6°	82.0°	.3 FPS	-.3 FPS
350	-7.4°	83.2°	.35 FPS	
400	-6.5°	84.0°	.4 FPS	-.4 FPS
450	-5.8°	84.7°	.45 FPS	
500	-5.2°	85.2°	.5 FPS	-.5 FPS
550	-4.7°	85.6°	.55 FPS	
600	-4.3°	86.0°	.6 FPS	-.6 FPS
650	-4°	86.3°	.65 FPS	
700	-3.7°	86.6°	.7 FPS	-.7 FPS
750	-3.5°	86.8°	.75 FPS	
800	-3.3°	87.0°	.8 FPS	-.8 FPS
850	-3.1°	87.2°		
900	-2.9°	87.3°	.9 FPS	-.9 FPS
950	-2.7°	87.5°		
1000	-2.6°	87.6°	1.0 FPS	-1.0 FPS

Figure 4-26.- PROX OPS cue card.

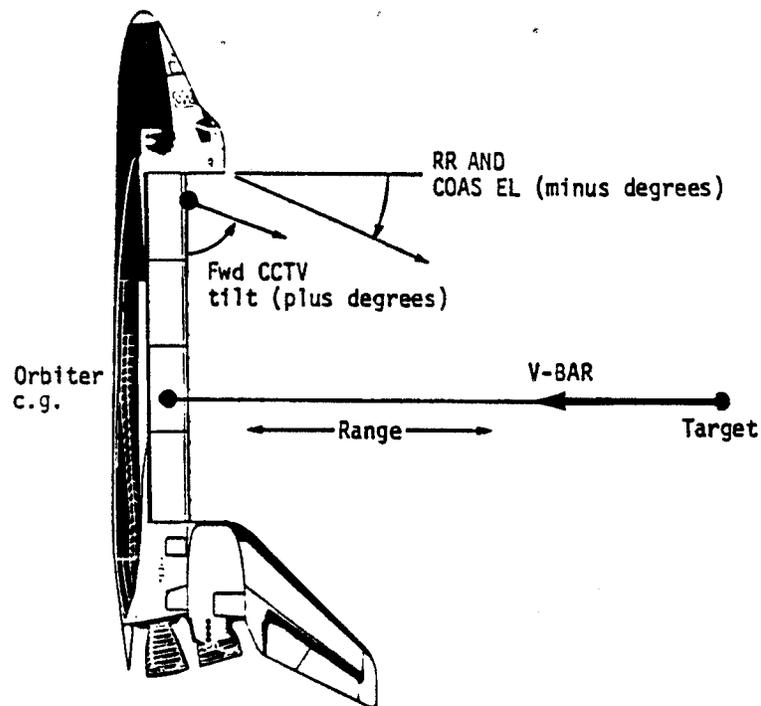


Figure 4-27.- PROX OPS sensor trigonometry.

4.3.6.3 Flyaround Velocity

This column specifies the actual relative speed (ft/s) of the Orbiter if it is in inertial hold performing a flyaround of the TGT. The value can be used to assist in estimating ΔV required to initiate or terminate such a MNVR.

4.3.6.4 V-BAR Approach Rate

This column is a generalized definition of desired R-DOT for the V-BAR approach, and is identical to the braking gates values discussed in section 4.1.64 in the RNDZ rationale narrative.

4.3.7 Breakout

See section 4.6 for selection procedure/rationale, and section 5.4.3 for actual execution procedure/rationale. The cue card may be called out post-MC1 (secs. 4.1.52 and 4.4.2).

4.4 FAILURE PROCEDURES

4.4.1 Loss of Star Tracker(s)

Since the STRK's are also used during IMU alignments throughout the flight, their operational status should be well determined by RNDZ day. Although an STRK could later fail at any moment, flight experience has shown that if the STRK is functioning properly prior to RNDZ day, it will continue to function properly.

The nominal RNDZ checklist provides options for -Y STRK pointing if the -Z STRK suddenly fails. At long ranges, loss of both STRK's leaves the Orbiter with-out sensor data unless COAS NAV (cue card, sec. 4.3.3) can be performed (TGT visibility is the driver here).

Although leading STRK failure modes involve highly visible hard failures, there are possible malfunctions involving unacceptable biases where the MCC would declare the STRK "failed" on ground data not readily apparent to the crew. This is considered highly unlikely, and if it occurs, it should do so well before RNDZ day.

Discussion of STRK fail cases post-Ti are found in the following section.

4.4.2 Radar Hard/Data Fail

For reference, table 4-2 shows a compendium of actions based on various sensor failure modes; it is already incorporated in FDF procedures and the rationale is presented in the following section. These actions are executed based on the following warnings:

- a. If NO sensor acquisition has occurred since the beginning of the RNDZ, breakout is at sunset (RNDZ OPS delay may be considered if sensor(s) can be fixed within reasonable time).
- b. If ANY sensor acquisition has occurred pre-Ti, but NONE post-Ti, perform breakout at MC2 + 20 minutes UNLESS TGT is visually or electronically acquired prior to that time.
- c. If ANY sensor acquisition has occurred post-Ti (pre-Ti sensor history is irrelevant), continue the RNDZ to MC2 + 22 minutes. If TGT is not visually or electronically acquired by that time, execute RNDZ breakout immediately.

TABLE 4-2.- RR/STRK STATUS/ACTION

Situation	Action (Post-Ti)
Nominal Sensors (good RR)	Use RR, ops normal
RR Hard Fail (-Z STRK good) (-Y STRK status irrelevant)	** Use -Z STRK * If -Z STRK fails to acquire in 5 min, then use COAS and continue attempts at -Z STRK acquisition
RR Hard Fail and -Z STRK Hard Fail (-Y STRK good)	** If target not within 1° of COAS center, * Perform COAS NAV until angle resides <0.05, then * Use -Y STRK (DAP B takes 3 min to get to attitude) * If no -Y STRK acq after 5 min return to -Z TGT track (3 min in DAP B) and take about five more COAS marks * Otherwise (i.e., good -Y STRK), after sunset (MC1 plus a few minutes), return to -Z target track and retarget MC2 after maneuver complete
RR Hard Fail, and -Z STRK Hard Fail, and -Y STRK suspect or Hard Fail	** Perform COAS NAV * Take about 5 marks at beginning of pass * Repeat near end of pass
RR no lock-on (RR good OR suspect), -Z STRK good, -Y STRK status N/A	** Use -Z STRK * Attempt AUTO TRACK acquisition, then back to GPC * If -Z STRK fails to acquire in 5 min, * use COAS NAV, and * continue -Z STRK acq attempts
RR suspect and -Z STRK suspect/fail -Y STRK status N/A	** Continue attempt RR acq in GPC ** Perform COAS NAV (about five marks) ** Attempt RR AUTO TRACK acq ** If no joy RR, * Attempt -Z STRK acq, * If no joy STRK, * Take five more COAS marks
No sensor acquisition pre-Ti	** Perform Ti Delay if sensors can be fixed within reasonable time

Post-Ti target acquisition can be accomplished through any one of four NAV sensors; the RR, the -Z or -Y STRK, or the COAS. All things considered, the RR is by far superior for RNDZ NAV purposes, but is also subject to the most single point failures, and is the most difficult to check out prior to the RNDZ activities (self-test pass or fail is not necessarily significant. See sec. 3.3.4.4). Either STRK is next in priority, since angle marks can be taken more accurately, more frequently, and with less propellant use than COAS marks. In addition, STRK's are typically used on a daily basis for IMU alignments, and so their operational status is known with a high degree of confidence prior to RNDZ initiation. The COAS is the last in priority, with no reasonable failure modes that would preclude its use.

In accordance with the relative usefulness of the sensors for NAV purposes, a hierarchy has been established for failure downmoding. A known RR failure is treated differently than a lack of TGT lock-on due to unknown causes. If the RR is known to be failed (mechanical problems with the Ku antenna, etc.), the first downmode is to the -Z STRK (see procedure in 4.1.44 in RNDZ rationale narrative). If the STRK is known to be failed, then the -Y STRK is the next choice. Before maneuvering, however, the COAS is used as a quality check on the NAV state. If necessary, COAS marks are taken to improve the NAV state accuracy and ensure that the target will be within the 1° small scan of the tracker, increasing the probability of acquisition. If the -Z STRK is thought to be working but fails to lock on, then NAV accuracy or TGT spectral characteristics (brightness, variability, etc.) are suspected to be the problem, so the -Y STRK is not anticipated to be an improvement. Thus, rather than wasting time in an attitude maneuver, COAS marks are taken, if possible. At the crew's discretion, -Z STRK acquisition can be reattempted.

Similarly, if the RR does not have a known failure, then lack of lock-on is assumed to be a result of NAV errors or insufficient signal return. To overcome NAV inaccuracy, manual slewing and acquisition with the RR are attempted first (sec. 3.3.4.6). Still failing to acquire, the downmode is to the -Z STRK. Even if the -Z STRK is known to be failed, in this situation the COAS will be used rather than the -Y STRK, since the -Y STRK acquisition attitude makes it impossible for the RR to lock on due to body blockage.

If no RR lock-on has been established by MC3, then at sunrise (usually ~7 minutes after MC3) a manual takeover is performed. MC3 and MC4 are not executed since no new sensor data has been incorporated since MC2, and also because it is considered imperative to establish proper LOS rates as early as possible. If visual acquisition is not available by MC4 + 5 minutes, a breakout MNVR must be performed ASAP. This MNVR is sized to ensure no recontact throughout the 3-sigma ellipse of dispersions.

The arrival of sunrise is a critical moment because at that point the TGT becomes visible and the procedure can begin. If the TGT is equipped with lights, the procedure can begin even earlier (the earlier the better).

When visual acquisition is accomplished, the Orbiter is pitched to bring the TGT to the COAS horizontal, and yawed until the LVLH yaw is zero. The pitch

allows for determination of in-plane errors, and the yaw is performed to unmask any planar errors. Having accomplished the pitch, it is possible to determine the "theta angle," which is the in-plane angle from the Orbiter V-bar to the target line of sight. From the associated table (fig. 4-29), the dispersion region can be determined.

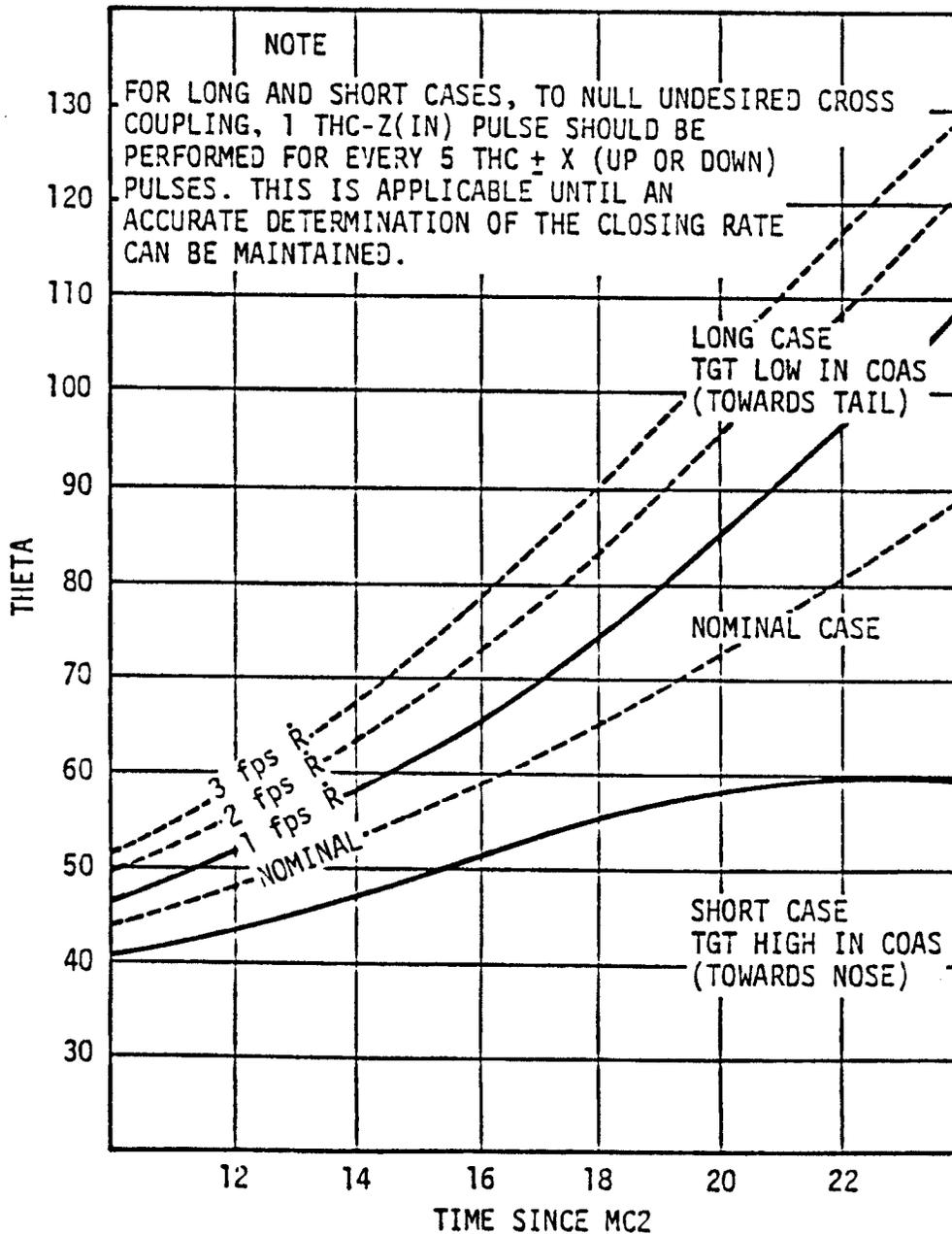


Figure 4-29.- Region determinator.

Note: The lines in figure 4-29 are empirically derived from analysis of a large number of ground simulations. They are valid for circular orbits only.

The logic behind the "theta" vs. "time since MC2" table (fig. 4-29) is as follows:

Prior to manual takeover the Orbiter attitude will follow a nominal time history, since without sensor data, NAV can only assume that a nominal trajectory is being flown. At sunrise, the NAV error will be suddenly exposed. As shown in figure 4-30, if the trajectory is short, the TGT will appear high in the COAS, and if the trajectory is long, the TGT will appear low. The great majority of cases will fall near enough to the nominal trajectory that nominal procedures can be followed. For sufficiently short or long trajectories, however, simulator experience has shown that nominal procedures will not result in a successful RNDZ, so special techniques must be used. The table delineates the boundaries of the "acceptably nominal" trajectories.

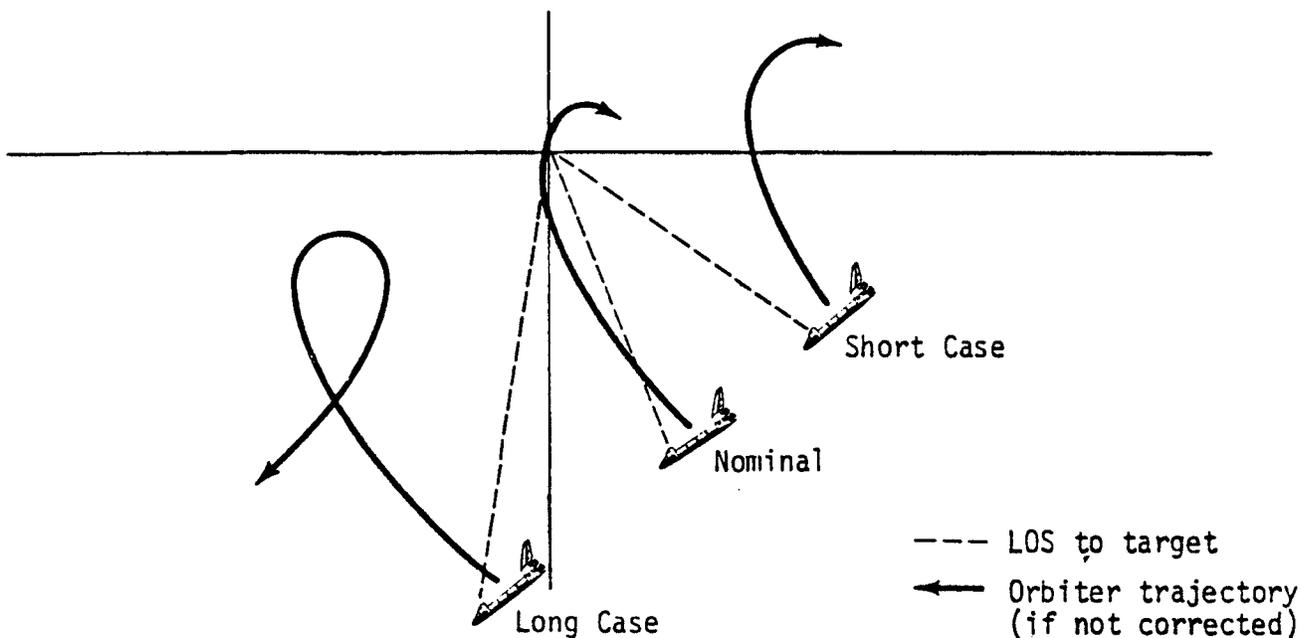


Figure 4-30.- Dispersed sunrise points.

For the family of trajectories that fall in the "short" category, it can be seen that many Orbiter +X corrections will be required to force the trajectory back towards the nominal path. Due to cross-coupling of X into +Z, this thrusting activity will tend to null the closing rate, and if not compensated for will turn a short case into a long case, as shown in figure 4-31. The final result of this is an unsuccessful RNDZ, since the change in range rate is difficult to detect with the RR failed, and the V-BAR arrival will be too far away to allow for closure within daylight. To compensate for this cross-coupling, the procedure calls for application of one Orbiter -Z pulse for every five $\pm X$ pulses (the theoretical background for this rule of thumb is found in sec. 3.8.2). Note that it is very easy on short cases to initially overcorrect with +X, requiring subsequent -X; both contribute to +Z coupling. An important procedural point (that can only be driven home in the simulator) is that it is necessary to make the $\pm X$ corrections when visual cues suggest that they are required. Anticipating help from orbital mechanics effects, or thinking that error is "in the right direction," will usually result in an unsuccessful RNDZ. Many of these trajectories seem to "fall off the cliff," if errors are not corrected relatively quickly.

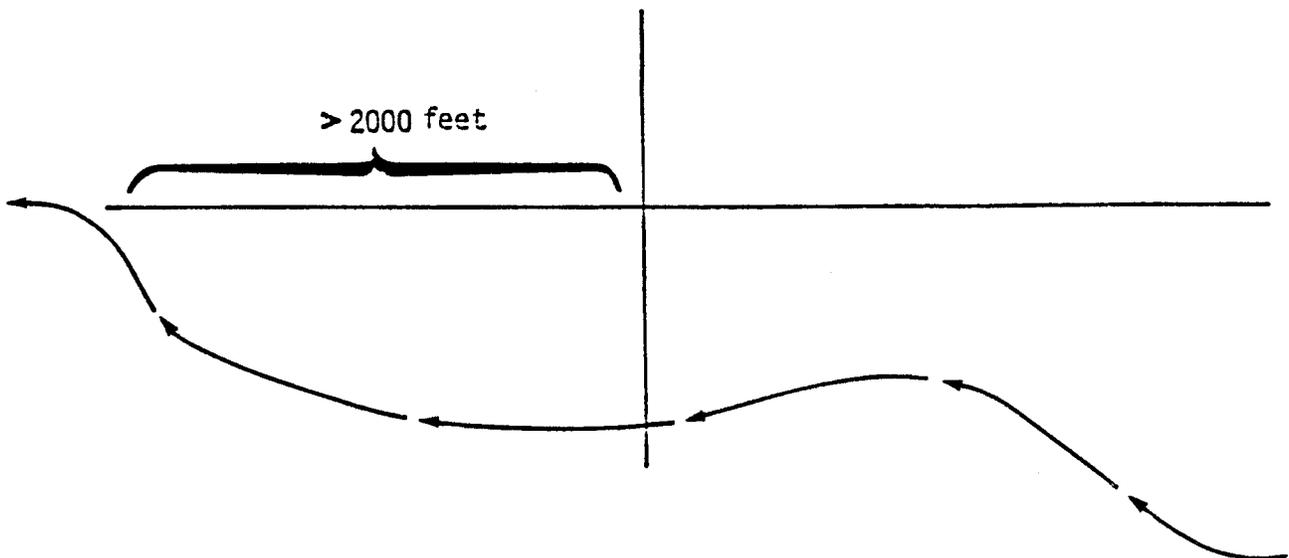


Figure 4-31.- Uncompensated coupling effects.

P R i t c h	ω_I deg/s	0.00	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
	ω_{LV} mrad/s	1.1	1.4	1.8	2.1	2.5	2.9	3.2	3.5	3.9	4.3	4.6

$$\Delta V \text{ (ft/s)} = \omega_{LV} \text{ (mrad/s)} \times \text{RANGE (kft)}$$

Figure 4-32.- Calculation of -X ΔV (THC - down) required to stop on V-BAR.

The family of trajectories that falls in the "long" category, if not specially handled, will also reach the V-BAR too far out to allow for closure before sunset. To deal with these cases, two major changes are made to the procedure. First, as soon as the theta error can be determined, an adjustment to the closing rate is made, based on data from the chart. Then, because attempting to maintain inertial LOS rates at zero would tend to undo the R-DOT correction, the Orbiter is pitched as required to keep the target centered in the COAS. However, allowing pitch rate to vary with the trajectory makes it impossible to determine a priori when V-BAR arrival will occur, and, in fact, some trajectories may not reach the V-BAR, even with the R-DOT correction. Therefore, it is necessary to monitor the flyaround rate by monitoring the Orbiter pitch rate. If the pitch rate ever drops down to zero prior to V-BAR arrival, it is necessary to put the Orbiter in inertial attitude hold and perform +X THC corrections as required to drive the trajectory to the V-BAR. Most of these cases, however, tend to reach the V-BAR with a fairly large altitude rate, and require significant -X thrusting to stabilize on the V-BAR (often 5 to 10 ft/s; see fig. 4-32). As in short cases, this thrusting will couple into +Z, so the same "one -Z per five \pm X" rule of thumb applies.

Just as short case trajectories are sensitive to certain variations in pilot technique, this group of trajectories requires special attention to several points. First, the pitch rate can and should be carefully matched with the vernier RCS (VRCS). Allowing the TGT to drift up or down in the COAS can mask the effects of trajectory dispersions, and tend to make it difficult to anticipate the size of the -X correction needed at the V-BAR. Second, the -X correction at the V-BAR should be made aggressively, based on estimated range at the V-BAR arrival and knowledge of the flyaround rate. For example, using the table in figure 4-32, a pitch rate of 0.1 deg/s at a range of 500 feet will require ~1.5 ft/s -X, and by the "1 per 5" rule, -0.3 ft/s -Z. Undercorrecting will result in a lofted trajectory that may or may not return to the V-BAR at an adequate range for comfortable, efficient stabilization. As in most problems of this nature, early correction of rate errors will reduce the required late corrections to a manageable level.

Notice that for a no-radar case there are not any real braking gates. A braking gate is a desired closing velocity at a specific distance from the TGT (a speed limit). In a no-radar case, range and range rate are found

empirically by measuring the change in TGT size over a period of time. Because of this inaccuracy, braking gates are not used on a no-radar case, but range rate should be monitored to ensure reasonable closing rates.

4.4.3 Loss of Verniers

The RNDZ checklist will call out the following procedure for loss of verniers:

Use nominal RNDZ DAP with TAIL ONLY CNTL from the beginning of the RNDZ sequence up to the NCC burn. Use NOSE and TAIL (full up) CNTL during and after the NCC burn.

This is based entirely on OMS/RCS PROP consumption. If MCC decides propellant quantities have sufficient margins, this control mode (and the NAV problems it entails - see sec. 3.2.1) can be waived and full control with PRCS can be selected.

4.4.4 Loss of Low Z Mode

With low Z mode the TGT will suffer less plume impingement effects. Loss of low-Z may impact expected TGT attitude and rates during final approach to grapple. However, RNDZ and PROX OPS would probably continue on the nominal timeline.

Certain payload separation MNVR's (e.g., Space Telescope) require use of low Z for contamination concerns. Unavailability of low Z mode may delay deployment until IFM restores capability or replanning can be accomplished.

4.4.5 Loss of Aft THC,RHC

For RNDZ and possibly long-range stationkeeping, operations can be conducted from the forward THC/RHC's; close range flying is unacceptable. The only reason to proceed with RNDZ/PROX OPS at all is if some IFM promises to restore aft capability.

4.4.6 Loss of EE CCTV

Since the EE CCTV is a crucial PROX OPS sensor (see sec. 3.3.5.5), its failure will seriously impact procedures. The TGT must be moved up over the right rear window for better visibility by the RMS operator. Since it then is no longer in the plume shadow, DAP must be moded to low Z. Aft PLB CCTV's can be used to monitor Z axis sense motion.

Alternative procedures involving use of the RMS elbow CCTV have not been worked out.

Note: Loss of PDRS results in effective loss of EE CCTV, although it is conceivable that the elbow CCTV could still be used while the RMS is stowed.

4.5 BACKOUT

Certain systems failures, as specified in the flight rules, may disallow Orbiter operations within 200 feet of a TGT (e.g., loss of translation capability in any axis or loss of redundant +Z capability). Under such conditions the Orbiter will move out to the 200-foot point, go to normal Z control mode (usually), and begin stationkeeping while the problems are being resolved. From this point the Orbiter will either resume approach or perform PROX OPS breakout.

Caution: Once back out at 200 feet, use of RR may remain inhibited due to payload restrictions on induced electric field intensity. Even in low power, the antenna can induce high currents before automatically dropping to bypass mode.

4.6 BREAKOUT

The "breakout" MNVR is a separation MNVR performed at an unplanned point in the RNDZ sequence. Nominal separation MNVR's are described in section 5.4.2; breakout MNVR's, described in detail in section 5.4.3, must be quick, simple, and safe across a wide variety of initial conditions.

Note that choice of NORM Z or LOW Z for the separation is made on a payload-specific basis, mainly on the issue of whether the payload must be preserved for later return (on a subsequent rendezvous).

Two distinct types of breakout MNVR's have been defined and documented in the FDF RNDZ books, Rendezvous and PROX OPS. Once a "breakout" has been called, the choice must be made as to which available procedure is to be executed. These, or alternate procedures such as the nominal separation or no burn at all, are chosen by the MCC based on table 4-3.

TABLE 4-3.- BREAKOUT MANEUVER SELECTION

Time frame	Procedure	Usual key driver
Pre-Ti	Usually no burn (FDO defines maneuver)	Orbiter systems
Ti (RNDZ abort)	Usually no burn (FDO defines maneuver)	Orbiter systems
*Delay (1-2 REV's)	Per Ti Delay pad	Orbiter systems
*Delay (24 hr)	Follows Ti Delay (FDO defines maneuver)	Orbiter systems
Ti to sunset (ASAP at sunset)	RNDZ breakout (3 ft/s OOP, followed by 3 ft/s retro 15 min later)	Sensors
Sunset to MC2	RNDZ breakout (3 ft/s OOP, followed by 3 ft/s retro 15 min later)	Orbiter systems
MC2 to MC3	None	Orbiter systems
MC3 to V-bar	RNDZ breakout (3 ft/s OOP, followed by 3 ft/s retro 15 min later)	Propellant quantities
V-bar (or near)	PROX OPS breakout (2 ft/s posigrade)	Propellant quantities OR other flight rule (e.g., GNC redundancy)
Elsewhere	Flight specific OR Generic Sep, Orb OPS C/L (1 ft/s away, 2 ft/s OOP, 3 ft/s posigrade)	Propellant quantities OR other flight rule (e.g., GNC redundancy)

4.6.1 Pre-Ti Breakout

Prior to Ti, a ground-computed breakout MNVR will be executed, if necessary, to guarantee a safe miss distance between the Orbiter and TGT. This is because prior to Ti, dispersions and the lack of a standard RNDZ profile prevent designing a "canned" breakout MNVR. The ground will compute a MNVR, if required, to ensure the Orbiter avoids the TGT by a safe distance. Typically, not executing a preplanned phasing MNVR will provide an acceptable miss distance.

4.6.2 Ti to V-BAR Breakout.

Between Ti and V-BAR arrival, the breakout MNVR sequence will be a 3 ft/s out-of-plane MNVR (nominally Orbiter $\pm Y$ body axis) away from the TGT plane, followed 15 minutes later by a 3 ft/s retrograde MNVR (Orbiter $+X$ body axis). This procedure is called "Rendezvous Breakout," and its rationale is found in section 5.4.3.1.

This breakout will be performed for the following reasons:

4.6.2.1 For Insufficient Propellant

For insufficient propellant or Orbiter system problems, the sequence will be initiated at orbital sunset, MC2, MC3, or ASAP if post-MC3. For reasons other than TGT sensor data, the breakout MNVR sequence should be initiated at the earliest acceptable point in the trajectory. Analysis indicates that orbital sunset to MC2, and at or post-MC3, are acceptable points in the trajectory to initiate the sequence. The earlier the sequence is initiated, the greater the TGT miss distance.

4.6.2.2 If No TGT Sensor Data

If no TGT sensor data (RR, STRK, COAS) has been obtained by orbital sunset, the sequence will be initiated at orbital sunset. With no TGT sensor data, the actual relative position between the Orbiter and TGT is not known with sufficient accuracy to complete the RNDZ. The sequence initiation was delayed until orbital sunset to allow maximum time for post-Ti sensors to obtain the TGT. The out-of-plane MNVR at sunset does not contribute to the TGT miss distance and could be deleted in real time as long as the retrograde MNVR is executed at orbital sunset plus 15 minutes.

4.6.2.3 If Only Pre-Ti TGT Sensor Data

If only pre-Ti TGT sensor data (RR, STRK, COAS) has been obtained, the sequence will be initiated no later than MC4 unless the TGT is acquired visually or with another sensor (RR is only current candidate). With pre-Ti TGT sensor data, trajectory dispersions are reduced. The sequence initiation can be delayed until MC4 and still provide an acceptable TGT miss distance. The retrograde MNVR does not contribute to the target miss distance and could be deleted in real time.

4.6.2.4 If Post-Ti TGT Sensor Data

If post-Ti TGT sensor data (RR, STRK, COAS) has been obtained, but is no longer available, the sequence will be initiated no later than MC4 plus 5 minutes unless the TGT is acquired visually or with another sensor (if all sensors are lost after this point, perform breakout immediately). With post-Ti TGT sensor data, the trajectory dispersions are reduced even more

and the sequence initiation can be delayed until MC4 plus five minutes while still providing an acceptable miss distance (500 ft c.m. to c.m.). Again, the retrograde MNVR does not contribute to the TGT miss distance and could be deleted in real time.

4.6.2.5 To Continue the RNDZ Post-MC4

To continue the RNDZ post-MC4 plus 5 minutes, visual acquisition or RR is required. Subsequently, if both of these are lost, the sequence will be initiated ASAP. Without visual acquisition or RR data (the crew is electronically "seeing" the TGT), it is not possible to continue manual control. The entire breakout MNVR sequence is required once manual control has been initiated.

4.6.3 Post-V-BAR Arrival

Post-V-BAR arrival the breakout MNVR will be as described in section 5.4.3.2, PROX OPS Breakout, with its rationale. Motivation for PROX OPS BREAKOUT can include propellant limits, flight rules invocation, or serious target or Orbiter systems failures.

4.7 RELATIVE MOTION PLOTS

Included in the RNDZ checklist is a set of Orbiter/TGT relative motion plots in TGT-centered polar coordinates (fig. 4-33). These are designed to allow the crew to plot their progress through the RNDZ and note any course deviations.

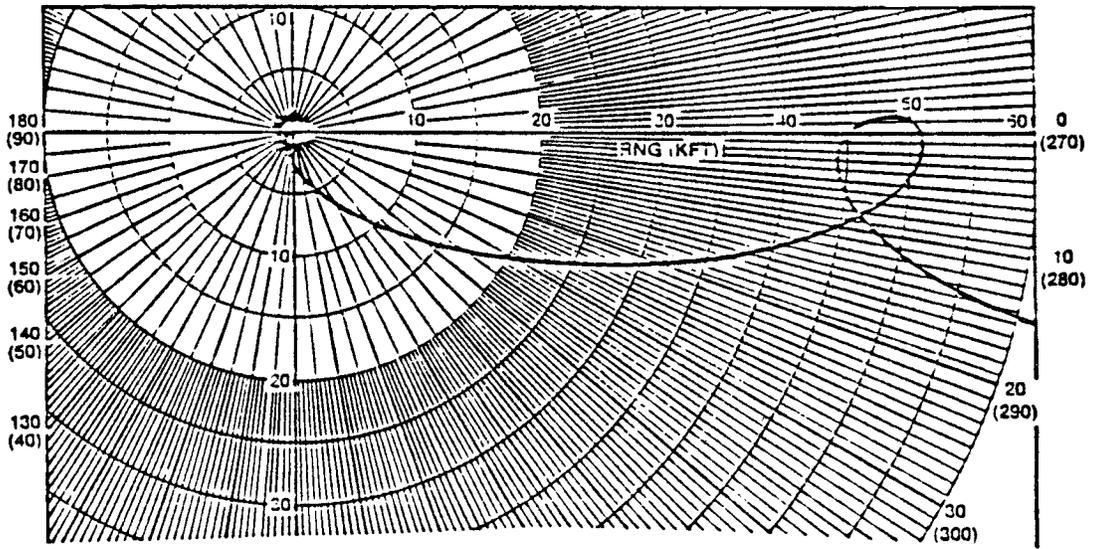
The specified angle assumes the Orbiter is in -Z axis TGT track. It can be read off the aft ADI; alternate values as seen on the forward ADI are also given.

4.8 FLIGHT DATA FILE DOCUMENTATION

A typical mission rendezvous or proximity operations book consists of a number of standard sections:

- Acronyms
- List of cue cards
- Contents
- Flight profile (charts)
- Detailed timelines (30 minutes per right-hand page) and pads

RELATIVE MOTION
FROM PRE TI



TERMINAL PHASE RELATIVE MOTION

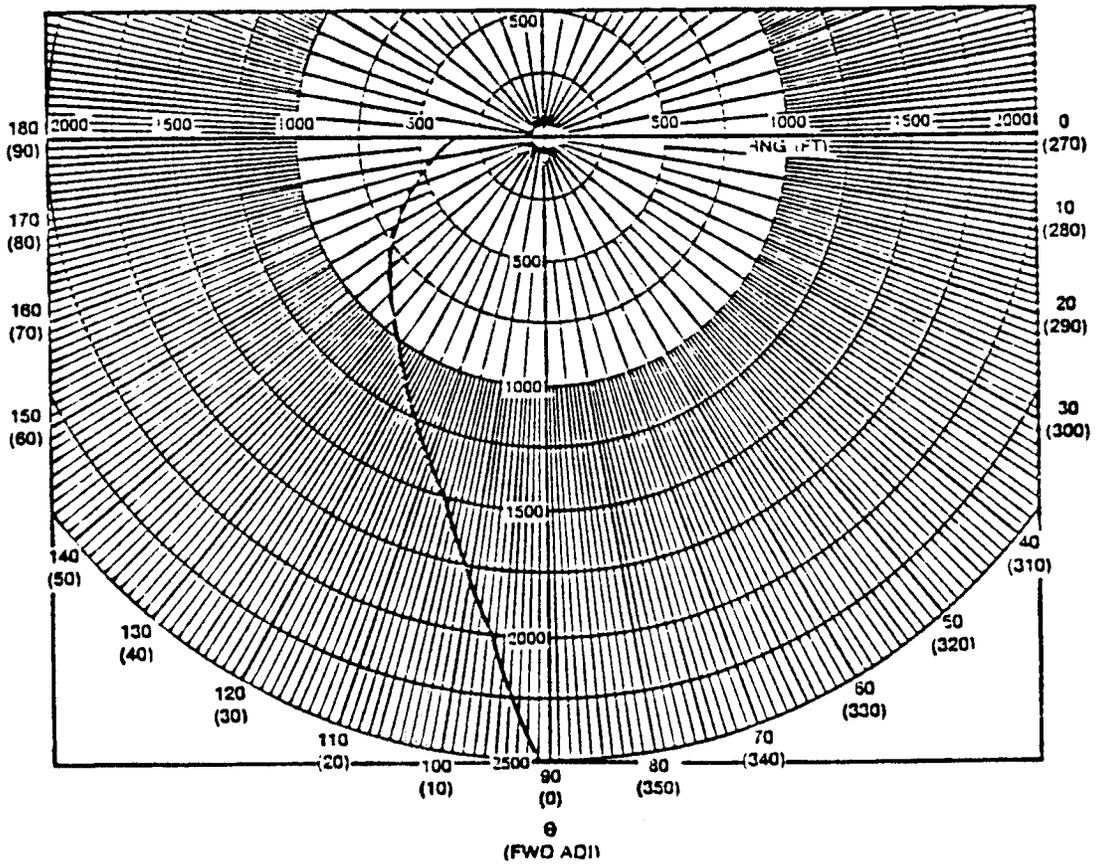


Figure 4-33.- Relative motion plots.

- Contingency operations (radar fail, loss of VRCS, DPS reconfiguration, RNDZ OMS burn, separations)
- Reference data (flight rules, targeting data, DAP configurations, relative motion plots, etc.)
- Ranging charts and rulers
- Cue cards (one set pure text, one set with velcro layout)
- Notes (baseline trajectory and mission day)

The rationale for location and format of deploy/SEP/RNDZ procedures is given below. This philosophy applies to all missions where there is a scheduled nominal rendezvous or a planned contingency rendezvous. Examples of the former are STS 41-C (Solar Max repair) or STS 51-L (Spartan-Halley). An example of the latter is STS-30 (Hubble Space Telescope (HST)). Some missions (such as Spartan or the HST) involve deploy of a payload early in the mission, followed by either a nominal rendezvous (Spartan) or a planned contingency rendezvous (HST) 2 or 3 days later. For this type of mission (which may generically be referred to as "Spartan-type missions"), the predeploy, deploy, separation, postseparation, and rendezvous procedures should all be contained in the Rendezvous book. The exact point during predeploy operations at which the crew switches to the RNDZ book, and the level of detail of the predeploy procedures contained in the RNDZ book, will be determined for each flight depending on its unique requirements. In addition, for very complex missions requiring a high degree of crew coordination or procedural integration, nondeploy related payload or scientific operations can be included to varying levels of detail, such as on STS 51-F (Spacelab 2/Plasma Diagnostics Package (PDP)) proximity operations.

For Spartan-type missions, there are two main considerations, format and location. The Rendezvous book format has been a standardized format since the early Apollo days, containing an event timeline and detailed procedures, along with information concerning relative motion, GSTDN and TDRS coverage, day/night cycles, DAP settings, navigation schedules, and a variety of contingency procedures, cue cards, and supporting reference data. Unlike other checklists, it is compatible with DM43's Rendezvous and Proximity Operations Procedures Master Data Base (i.e., a radar acquisition procedure in the deploy section looks similar to that which the crew would see in the rendezvous section). As such, the format would be the same for pre- and postdeploy operations; it is used during crew and flight controller training, integrated sims, real-time support, and on-orbit operations.

Many payloads are very sensitive to contingencies during deploy, and most deploys are tied to specific times, lighting, or other trajectory events, such as particular beta angle or TDRS acquisition for a specified period of time pre- and/or postdeploy. Some deploy contingencies requiring special procedures are: unavailability of the low Z DAP mode; no-RMS deploy; single-joint RMS deploy; and late deploy. Sometimes these procedures are so different from the nominal, or are otherwise so complex or critical, that

completely new contingency sections of the book need to be written. The rendezvous format easily accommodates these problems with a minimum of confusion and maximum crew coordination. Finally, the rendezvous format easily accommodates the integration of systems procedures (RMS, communications, OMS/RCS, payload systems, etc.).

From the preceding paragraphs it is possible to see many reasons why it is important that deploy and separation procedures be incorporated in the Rendezvous book for Spartan-type missions. There are, however, other reasons. It is highly desirable to have in one book all rendezvous-related procedures; i.e., those involving the integrated rendezvous GN&C hardware and software systems, especially when dealing with a two (or more) body problem. This provides the maximum continuity between deploy/separation and rendezvous procedures, especially during those critical moments just prior to and following the actual deploy when the minimum amount of confusion and the maximum possible level of crew and flight controller coordination is mandatory to ensure that the deploy is properly accomplished for both reasons of mission success and crew safety. Additionally, DM43 has means to establish a performance history of the sensors and navigation system. Also, it is easier for both the crew and flight controllers if all deploy and rendezvous maneuver pads are in one book, along with the propellant GO/NO GO pads and flight rules.

There is a need to check out the navigation sensors (radar and star tracker) at an early point in the mission (immediately following deploy), not only to satisfy the MCC that the sensor itself and the associated hardware and software are working properly, but also to get an idea of how the sensor interacts with the individual payload. In other words, was there any problem in acquiring the target, and did it stay locked on out to the expected range? Were there any problems in tracking the target, perhaps caused by its rotation, surface, or RF characteristics? These are among the target RF and optical characteristics and questions that can have an impact on the rendezvous timeline and procedures, and can be confirmed by using the sensors postdeploy. On some missions, there are nominally planned phasing burns, or other targeted maneuvers, designed to maintain the Orbiter within a desired area "near" (6 to 12 miles) the payload for a period of time up to several hours postdeploy. It is therefore critical to acquire the target and begin navigating immediately following deploy, and the best way to do this is to keep the crew in a checklist with the rendezvous format (preferably the Rendezvous book) throughout the entire procedure, thus ensuring maximum continuity and crew coordination.

In summary, by having a completely integrated checklist with all predeploy, deploy, separation, postseparation, and rendezvous procedures in one book as described above, the best possible level of mission support can be provided, both preflight and real time. This is a philosophy and methodology which has withstood the test of time and the test of actual on-orbit operations. It works well both for the people who develop techniques and provide real-time support, and for the people who use the procedures on orbit. But most importantly, it offers the best assurance of accomplishing the mission.

4.10 In-Flight C/L Utilization

Normally there will be three copies of the rendezvous checklist on board the Orbiter. They are stowed in a middeck locker for use after orbit operations begin. A sample cover sheet for such a checklist is shown in figure 4-34.

Crew handling of the checklist follows STS norms and standards. Cue cards are positioned at the disgression of the crewmembers using them. CCTV monitor overlays are on clear plastic with velcro tabs for affixing to the CCTV monitors. MCC calls will be made to the specific page number of the checklist. The crew will be familiar with this checklist from ground simulation activities.

National Space Transportation System	JSC-20848
FLIGHT DATA FILE	
Contingency Rendezvous	
Don't Leave Earth Without It	
Mission Operations Directorate Flight Design & Dynamics Division	
Generic November 21, 1986	
 National Aeronautics and Space Administration Lyndon B. Johnson Space Center Houston, Texas	

Figure 4-34.- FDF Rendezvous Checklist (Typical)

SECTION 5
PROXIMITY OPERATIONS TECHNIQUES RATIONALE

PROX OPS include stationkeeping, flyarounds, final approach to grapple, and separation.

One mission commander had made this extremely perceptive observation about PROX OPS: "This is not just a knowledge type operation, it's a skill-type operation that requires continuous training to develop and maintain at skill level. Knowing how to do it is not enough. You have to develop the skill so you can do it time and time again and be repeatable."

5.1 STATIONKEEPING

During PROX OPS, stationkeeping techniques are required to maintain the Orbiter in a desired position relative to the TGT, either in a TGT-inertial or LVLH-referenced frame. The zone of proximity stationkeeping operations is limited to ranges and relative velocities within which RNDZ operations are not required to achieve repeated close approach. Typically, $R \leq 1000$ feet, with rates in each axis ≤ 1 ft/s.

Under the requirement that the Orbiter maintain a position in the TGT-centered LVLH frame, the Orbiter is usually positioned along the TGT +V-BAR, with UNIV PTG controlling the Orbiter attitude as -X to Earth and omicron of zero (PLB to TGT). Thus, the TGT will be trailing the Orbiter. Assuming zero differential drag between the Orbiter and the TGT, V-BAR positions are the only ones which are theoretically stable. This results in the most efficient type of stationkeeping, because minimal propellant is required to maintain the Orbiter c.m. at the same altitude and coplanar with the target c.m. SES experience shows one can maintain a position at 1000 ± 30 feet on the V-BAR for about 100 pounds of propellant per REV, using an optimum VCRS/PRCS technique (NORM Z).

Stationkeeping on the TGT radius vector (R-BAR) is usually undesirable due to operational complexity and the high propellant usage penalty required to stay on the R-BAR (theoretical analysis provides a rule of thumb for extra usage, above and beyond normal stationkeeping usage, as approximately 0.5 lb/ft of separation, per REV).

5.1.1 Stationkeeping Control

During stationkeeping activities, the crew must judge when Orbiter attitude and/or translation corrections are necessary, and make corrections manually.

5.1.1.1 Attitude Control

Depending on the type of stationkeeping, the Orbiter attitude is maintained automatically either in an inertial or an Earth TRK mode. The Orbiter attitude control system, which provides the Orbiter with the capability to maintain the proper attitude for stationkeeping, consists of the UNIV PTG function, the LVLH mode, and the inertial attitude hold mode.

The size of the ATT DB is also of concern in stationkeeping since it must be selected based on a compromise between two conflicting trends. For attitude considerations alone, the basic tradeoff has always been between narrow DB's (which give high attitude precision and incur high propellant usage for attitude control) and wide DB's (which saves propellant for attitude control). However, from the point of view of maintaining a desired stationkeeping position, a narrow DB allows the pilot to more easily discern actual position errors (and make immediate translation corrections) while a relatively large DB tends to mask increasing position errors. If a large altitude differential is allowed to build up, this creates relative orbital mechanics forces which drive the Orbiter off its desired position and requires costly translation burns to counteract. Thus the most economical DB must be selected based on a compromise between attitude control propellant usage (which suggests narrower DB's) and translation propellant usage. Normally, 2° PRCS and 1° VRCS DB's are used as the "best compromise." See section 3.2.1.

Universal Pointing - UNIV PTG, which is defined MM201 keyboard entries and activated via the AUTO pb, provides for maintaining a specified attitude with respect to a reference frame (such as LOS to center of Earth). The main contribution of UNIV PTG to stationkeeping is this ability to automatically maintain a desired attitude or to maneuver to a specified attitude. This reduces the number of degrees of freedom of the Orbiter from six to three (translation only), so the crewmember can concentrate on a more manageable piloting task.

LVLH Mode - The LVLH mode keeps the Orbiter in a fixed position relative to a rotating reference frame.

An example of use is an out-of-plane flyaround in the local horizontal plane of a TGT which is LVLH-stabilized. The MNVR is performed with pulses in the Orbiter roll axis, while pitch and yaw are automatically maintained relative to LVLH (see section 5.2.2).

Inertial hold - The inertial attitude hold mode is needed when the Orbiter is required to be fixed in the inertial frame. The inertial attitude hold mode is primarily for close-in stationkeeping or approach to grapple to an inertially stabilized payload.

5.1.1.2 Translation Control

During stationkeeping, translation control is necessary to help maintain the position of the Orbiter relative to the TGT. The primary purpose of the

translation control is to maintain the Orbiter c.m. in the vicinity of the target V-BAR within some predetermined range limits.

Using COAS cross-field-of-view drift, or RR digital angle rates, or CCTV, a crewmember knows the direction of normal LOS rates and can perform corrections using the THC. RR data may provide much more precise readings which allow the crewmember to avoid overshooting/undershooting corrections and thus avoid rates propagating into large trajectory dispersions. In the Orbiter body frame, these rates represent the normal to the LOS (NLOS) motion of the Orbiter trajectory relative to the TGT, and thus the required information for making NLOS translation corrections to the trajectory. Also, by appropriate attitude orientation of the Orbiter, the EL and AZ will represent the Orbiter in-plane and out-of-plane position, respectively, of the Orbiter relative to the TGT V-BAR.

A confined ("tight") form of stationkeeping performed during short and medium range ($R < 1000$ ft) operations maintains the Orbiter within relatively small limits (e.g., ATT DB $\pm 1^\circ$) around the optimum stationkeeping point by appropriate thrusting in all Orbiter axes. A less confined form of manual stationkeeping ("loose") used during medium and long range ($R > 1000$ ft) operations makes more efficient use of orbital mechanics forces as an aid to translation control, thereby reducing the need for translating in certain Orbiter axes.

The two basic types of translation guidance are automatic and visual. This refers to the method of determining required corrections, which are then always executed by the crew manually.

- Automatic translation guidance is accomplished by using navigated (i.e., GPC filter processed) relative state data to determine where crew-executed translation inputs are required for relative position corrections. The sensor data is used to update the relative state, which is then used to compute corrective MNVR's based on the orbit targeting algorithms.
- Visual translation guidance is accomplished by crew processing of TGT relative position information for determination of the approximate translation corrections. This relative state information comes from direct visual contact with the TGT (NLOS sense and approximate rates), and from raw RR data for LOS/NLOS value and rates information.

5.1.2 Classification of Techniques

For convenience, stationkeeping operations are classified by range (close in, short, medium, and long), and there are significant differences between these techniques used at different ranges. These differences are summarized in tables 5-1 and 5-2.

TABLE 5-1.- SUMMARY OF STATIONKEEPING CLASSIFICATIONS

Type	Close-in	Short	Medium	Long
Range	~35 ft	< 200 ft	200-1000 ft	1000 - 2000 ft
Duration (roughly)	≤ 1 rev	≤ 1 rev	1-2 rev's	2 revs to 1 day
Primary source of relative state information	Eyeball, EE CCTV	CCTV, RR, COAS + eyeball	CCTV, RR, COAS + eyeball	CCTV, RR, COAS + eyeball
Direct visual contact*	Required	Required	Required **	Desirable **
Orbital mechanics effects on maneuvers	Ignored	Ignored	Utilized	Efficiently utilized
Plume impingement concerns	Usually in quiet zone	Significant	Usually insignificant	Insignificant
Control technique	<ul style="list-style-type: none"> • Manual • Tight 	<ul style="list-style-type: none"> • Manual • Tight 	<ul style="list-style-type: none"> • Manual • Tight or loose 	<ul style="list-style-type: none"> • Automatic (elliptical) • Manual (loose)
Application	<ul style="list-style-type: none"> • Trim/align relative ATT for grapple/manhandling • 3 body OPS(MMU) • Photography/activation of disabled PL 	<ul style="list-style-type: none"> • Final stage of retrieval • Short term TGT checkout • Set up proper Orbiter/TGT geometry • 3 body OPS (MMU) 	<ul style="list-style-type: none"> • Final approach preparation • Short term TGT checkout • Three-body operations (MMU) • RMS preparation • Waiting for proper lighting • Troubleshoot Orbiter problems 	<ul style="list-style-type: none"> • Stand off • Long term TGT checkout

*Must have RR or visual/CCTV contact at all times.

**TGT must have lights or reflectors if night operations required.

Momentary loss of contact acceptable if under stable conditions, precise stationkeeping.

TABLE 5-2.- SUMMARY OF STATIONKEEPING CONTROL

Type	Close-in	Short	Medium	Long
Range	~ 35 ft	< 200 ft	200-1000 ft	1000 - 2000 ft
RMS	Ready to grapple	Ready to grapple	Ready to grapple	Stowed
Attitude hold	As required (combination of free/IAH or free/LVLH)	Usually matched to TGT	LVLH with -Z toward TGT	LVLH with -Z toward TGT
Orbiter X axis	As required	As required for approach	In TGT orbital plane	In TGT orbital plane
DAP	Usually NORM Z	LOW Z	NORM Z if outside plume sphere of influence	NORM Z

5.1.2.1 Close In

Close in stationkeeping techniques are required after the Orbiter has achieved a stable position near the TGT. Alignment with the desired TGT axis may or may not have been achieved.

Since close-in stationkeeping is done at 35 feet, orbital mechanics effects are ignored. Flying is done strictly from a combination of out-the-window and RMS EE CCTV camera views, still in the -Z sense.

At 35 feet, most payloads will remain in the "quiet zone," safe from plume impingement effects. Therefore all operations can be done in the "norm Z" mode. However, for very large PL's, such as the Hubble Space Telescope (HST) or LDEF, low Z may be necessary, especially if some type of Orbiter/TGT alignment maneuver is required. Also, if the payload drifts forward or aft of the "quiet zone," low Z should be selected until it resumes its position over the PLB.

Close-in stationkeeping is a "tight" stationkeeping technique, which, although easy to fly, requires the pilot's constant attention. Its common uses are waiting for proper PL geometry for grapple or preparing for final Orbiter/TGT alignment maneuvers, MMU flyover operations, or close-inspection activation of a disabled payload.

5.1.2.2 Short Range

Short range stationkeeping techniques are generally required after the Orbiter has already been positioned on the correct TGT final approach axis (i.e., that axis along which the Orbiter must approach in order to execute RMS grapple), or in the case of checkout operations, on any designated TGT axis. They may also be required immediately after TGT release.

The range is generally within the plume sphere of influence ($60 \text{ ft} < R < 200 \text{ ft}$). At these ranges, orbital mechanics effects can be effectively ignored. The time interval associated with close-in operations is usually less than 1 orbit.

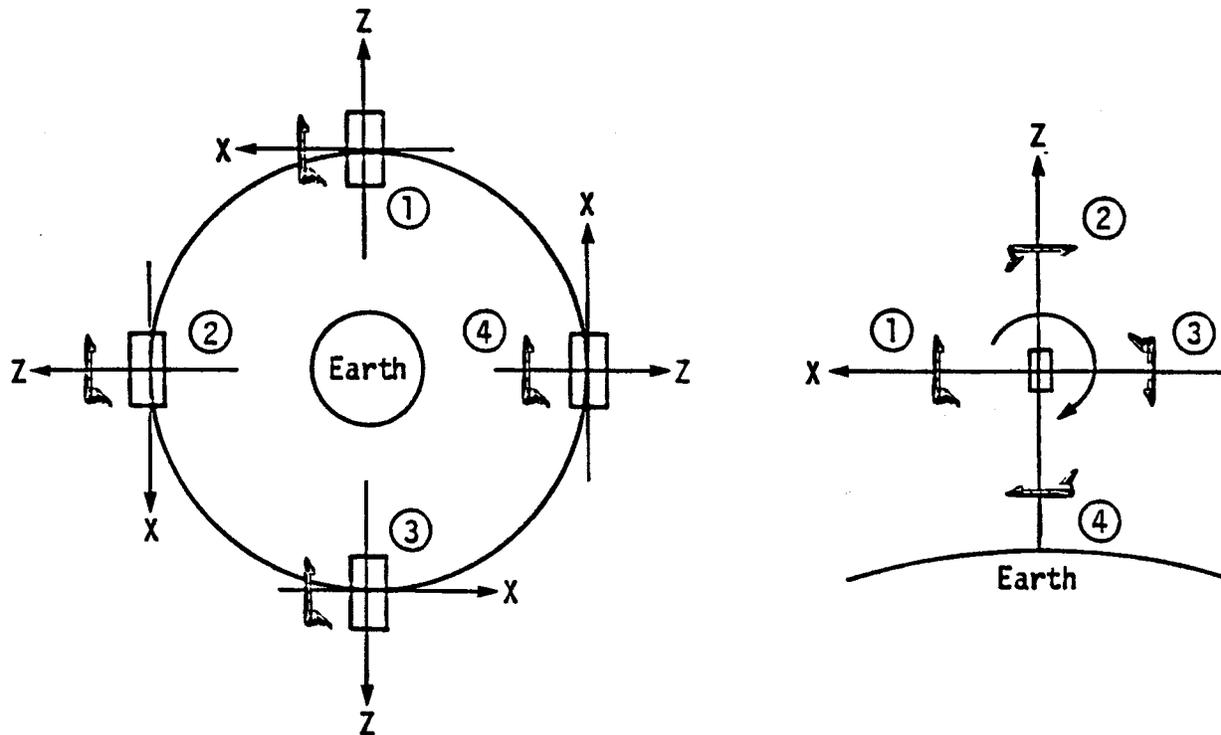
Two primary tasks involved during short range operations are matching the attitude rates of the Orbiter with those of the TGT (to within 0.1° deg/s and translating to maintain the correct relative position on the desired TGT axis. Thus, short-range stationkeeping generally requires visual translation guidance techniques.

"Tight" stationkeeping is the suitable technique used for short-range operations, which put emphasis on the use of the COAS for maintaining the Orbiter relative position on the desired TGT axis. The CCTV's are the primary source of LOS control during the last 200 feet of the final approach to grapple (see figs. 3-25 and 3-27). After the RR loses lock, they also become the primary source of range and range rate polarity information.

The different types of short-range stationkeeping techniques are:

- Orbiter stationkeeping with respect to an inertially stabilized TGT
- Orbiter stationkeeping with respect to a TGT fixed in the LVLH frame (while rotating at orbit rate).
- Orbiter stationkeeping with respect to a TGT rotating at an arbitrary rate relative to the LVLH frame or the inertial frame.

5.1.2.2.1 Inertially stabilized target.- This method presumes that the TGT is inertially stabilized, with the aid of some type of control system, or is spin-stabilized (fig. 5-1). In order to keep the same relative attitude geometry, the Orbiter must also maintain inertial hold. This then requires that the Orbiter translate continuously (with respect to the LVLH frame centered on the TGT) to stay on the desired TGT axis and maintain the desired range.

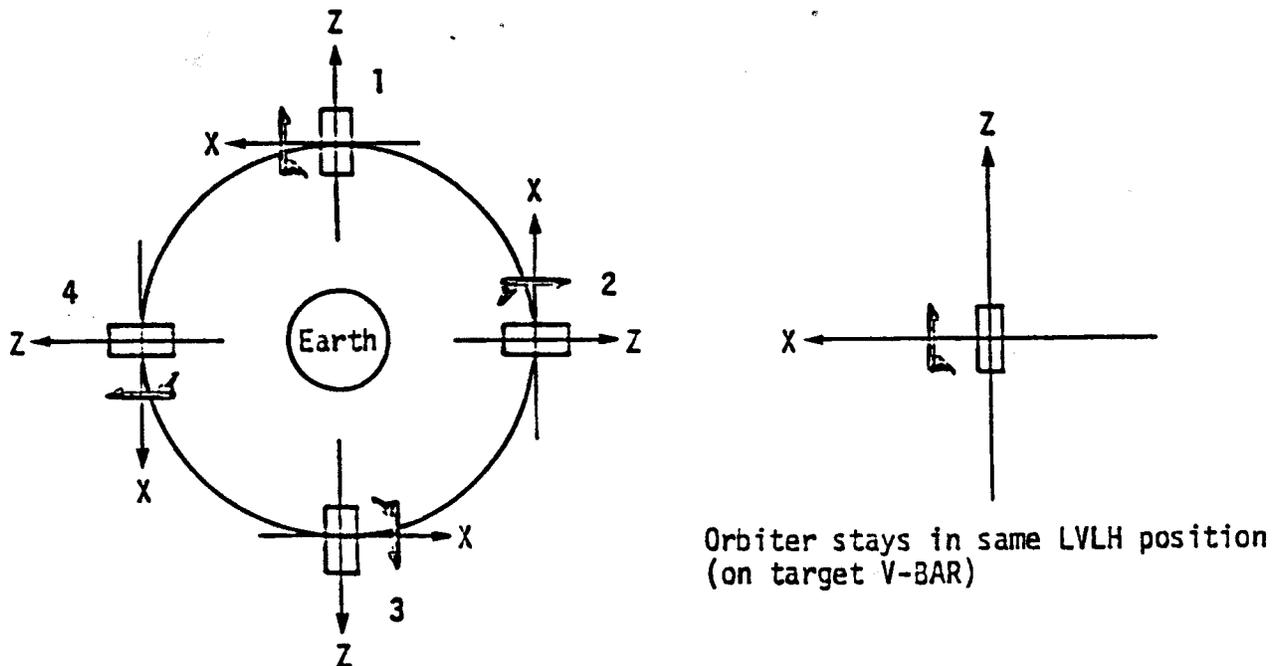


Stationkeeping WRT inertially stabilized target

Figure 5-1.- Inertially stabilized TGT.

The Orbiter DAP automatically maintains inertial hold, while the crew uses the COAS and CCTV for NLOS and LOS translation correction information.

5.1.2.2.2 Target attitude fixed relative to LVLH frame.- A TGT may be maintaining a constant attitude relative to the LVLH frame (and therefore rotating in the inertial frame at orbit rate). The TGT attitude may be controlled either actively with an attitude control system or passively by gravity gradient torques. In either case, the Orbiter maintains a fixed position and attitude with respect to the TGT LVLH reference frame (fig. 5-2).



Station keeping WRT target rotating
in inertial frame at Orbital rate
(i.e., target attitude fixed relative
to LVLH frame)

Figure 5-2.- TGT fixed in LVLH reference frame.

Orbiter attitude is controlled automatically by either UNIV PTG (with selection of a proper Orbiter body vector pointed at the Earth) or by selection of the LVLH mode (UNIV PTG is the preferred technique). Translation is controlled manually as in the previous case; however, the amount of thrusting required is considerably reduced, due to the stable nature of LVLH fixed position stationkeeping.

Note: This applies only if the Orbiter is close to the V-BAR of the TGT. If we have LVLH stationkeeping with a large out-of-plane offset, and/or above/below the V-BAR, then this does not apply.

5.1.2.2.3 TGT rotating at arbitrary rate.- Under certain circumstances, the Orbiter may be required to perform short-range stationkeeping with a TGT which is rotating at an arbitrary rate about an arbitrary axis, relative to the LVLH frame. This type of stationkeeping would be needed if the TGT experienced the loss of its control system (active system failed, or passive system disturbed by some external torque such as plume impingement) causing the TGT to rotate at an arbitrary rate inertially about a principal axis of inertia, thus making it difficult for the Orbiter to initiate grapple procedures.

5.1.2.3 Medium Range

Medium-range stationkeeping is required primarily during preparation for final approach, and generally at a range outside of the TGT plume sphere of influence (approximately $200 < R < 1000$ ft). Other situations which may require medium-range stationkeeping operations include three-body operations (such as operations with an MMU crewmember), RMS activation, delay to await proper final approach lighting conditions, or troubleshooting Orbiter systems problems. The time period associated with medium-range stationkeeping is approximately one to two orbits.

Medium-range operations are controlled using manual translation techniques. The technique emphasizes maintenance of the c.m. of the Orbiter about the $TGT \pm V\text{-BAR}$ and direct visual contact with the TGT (i.e., tight stationkeeping as described in section 5.1.2.2). Since the CCTV is relatively inaccurate and ineffective over this range interval, the primary source of relative state information is the radar. With a visible TGT, the COAS and CCTV would still be useful for NLOS position determination.

For medium range, brief loss of direct visual contact is acceptable as long as stable stationkeeping has already been established. This was done on 51-F when loss of contact was approximately 4 minutes. This should be considered the longest allowable "blind" period.

5.1.2.4 Long Range

Long-range stationkeeping becomes appropriate during long-term ground or internal payload checkout and/or activation, or during three-body operations where a free-flyer is sent over from the Orbiter to perform some payload-related task. The ranges associated with long-range operations are between 1000 feet and radar acquisition range (however, for ranges greater than approximately 2000 feet the stationkeeping would not be considered a pure PROX OPS task and a rendezvous would most likely be required). The time period may range from two orbits to approximately 1 day.

Long-range stationkeeping operations can be automatically controlled, relying primarily on the use of navigated state data. For long-range stationkeeping the TGT appears visually as a point source of light, and direct uninterrupted visual contact with the TGT may not be possible (e.g., night time stationkeeping). However, the radar can provide the majority of the required relative position information. Use of one of the manual V-BAR control techniques is possible if raw radar data is available. Direct visual contact would serve as a useful supplement to the radar, but would not be sufficient alone as a source of long-range stationkeeping information (range and rates are needed).

For longer ranges and longer stationkeeping periods, manual techniques become somewhat laborious and expensive, and it is desirable to utilize some form of automated techniques whereby the Orbiter NAV system is utilized to determine when corrective maneuvers are required. The radar system is still required as a sensor for purposes of keeping the REL Orbiter/TGT SV current. A typical AUTO technique (fig. 5-3) uses an algorithm which attempts to maintain the Orbiter c.m. within some predefined boundary centered at some range on the TGT V-BAR. Whenever the Orbiter c.m. approaches the boundary, a maneuver based upon the current navigated REL state is computed and executed to drive the c.m. back to the center. Upon arriving at the center, a maneuver is computed and executed to null all rates relative to the TGT. The process repeats itself again after the Orbiter c.m. again drifts out to the boundary.

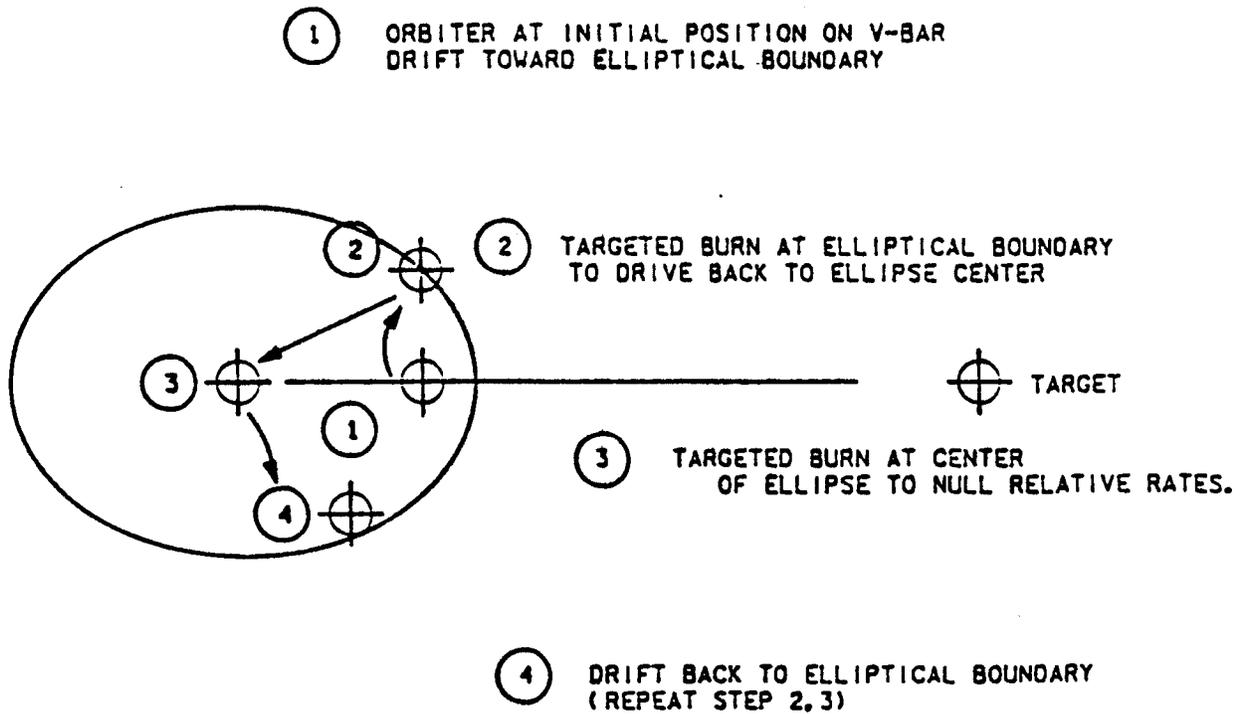


Figure 5-3.- Point stationkeeping.

5.1.2.5 Very Long Range

Under certain circumstances it may be desirable to perform stationkeeping at ranges from 1 mile to maximum radar track range and for periods of several REV's to a full day. In practice it has always been preferred to initiate a slow separation and perform another rendezvous the following day. However, requirements may force such very long-range stationkeeping and its resulting complications (e.g., 24-hour crew awake cycles and intermittent TDRS COMM). This falls outside of true PROX OPS.

5.1.3 Operational Groundrules and Constraints

For planning actual stationkeeping operations, the following groundrules and constraints should be observed (source, MOD memo DM4-86-62, Nov. 25, 1986).

Manual stationkeeping on the V-BAR axis for ranges on the order of or less than 1000 feet may be planned for a duration not to exceed a full crew work-day, (i.e., Crew Scheduling Constraints, Crew Procedures Management Plan, appendix K). This would require dedication of two qualified crewmembers and could not be scheduled on consecutive days. Due to disturbance from the FRCS firings, stationkeeping should not occur when any member of the crew has a sleep shift. This stationkeeping could be further limited by forward RCS propellant limitations which depend on other mission activities and details of the mission specific stationkeeping activities such as low-Z stationkeeping, failed VRCS, etc.

As a gauging point, it should be noted that with a full forward RCS loading available for the stationkeeping activity, the duration of the stationkeeping on the V-BAR will be limited to less than 20 hours due to stationkeeping costs of about 100 pounds per revolution plus retrieval at the end of the crew day followed by redeployment for additional stationkeeping. Stationkeeping will cost considerably more if not on the V-BAR.

5.2 FLYAROUND/TRANSITION

Flyaround is a PROX OPS task which generally involves maneuvering the Orbiter (active vehicle) from one point to another point relative to the TGT (passive vehicle). In particular, flyarounds require that the Orbiter, with appropriate translation corrections, maintain approximate constant range from a TGT while moving from one relative position to another in the TGT LVLH reference frame. Generally, the Orbiter maintains a specified body vector pointed toward the TGT throughout this phase. This axis is generally the Orbiter -Z axis since it provides COAS LOS TGT visibility and is the optimum radar track axis (fig. 5-4).

"Transition" is more general in scope in that it includes any operation which results in Orbiter movement from one point to any arbitrary point relative to the TGT in the TGT LVLH reference frame (i.e., range is not

necessarily maintained constant). Whereas flyaround maneuvers are generally flown in a manual mode since they require constant maneuvering, transition maneuvers may be automatically targeted.

The requirement to perform a transition or a flyaround may result from several situations such as the need to perform payload inspection, the requirement to support detached PL experiment operations by appropriate Orbiter relative positioning, or the requirement to move from a final RNDZ point (initial stationkeeping point) to a final stationkeeping point from which grappling operations can be initiated.

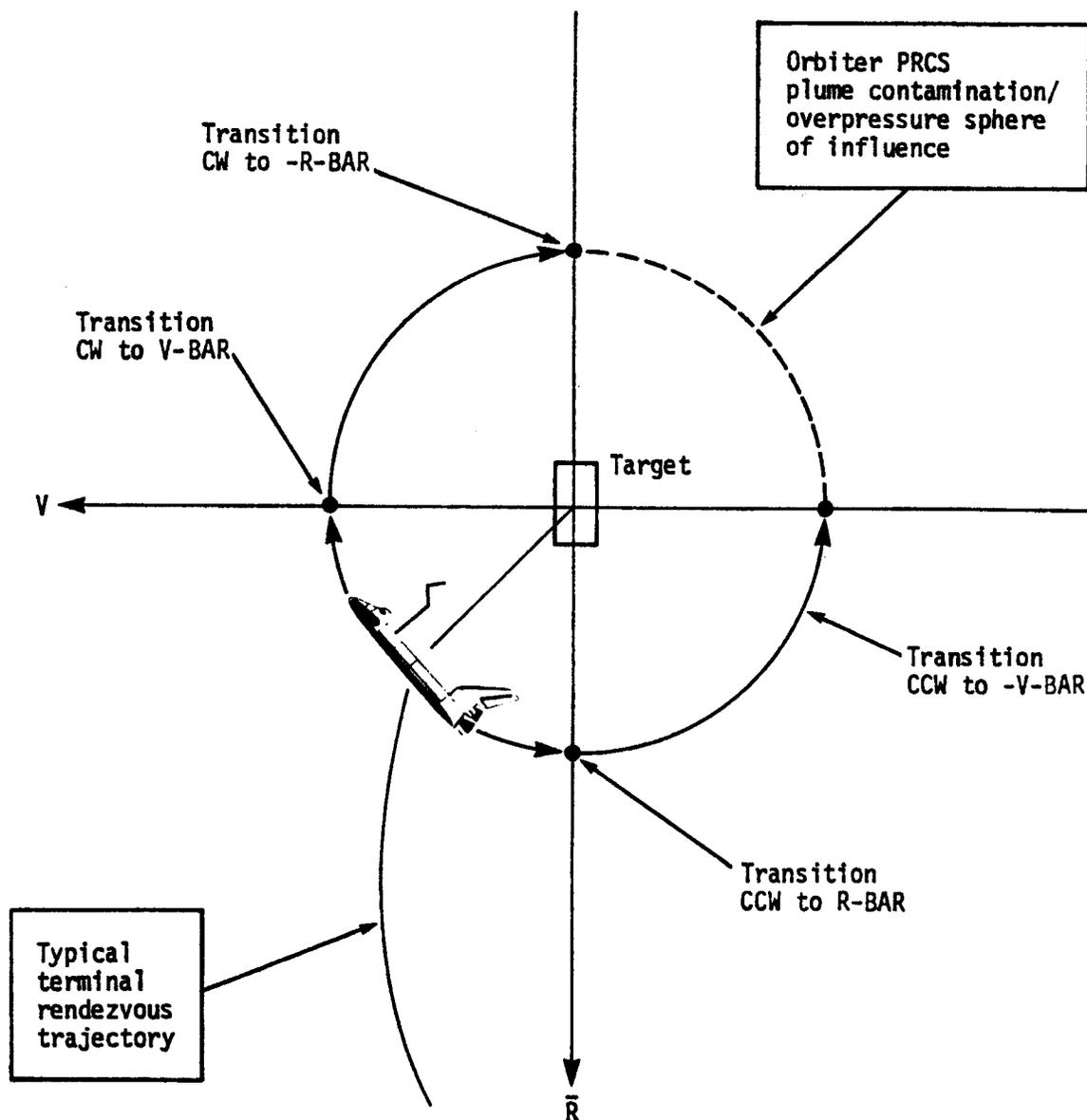


Figure 5-4.- Transition geometry.

Procedurally, the orbit rate flyaround requires that the Orbiter initiate, by "seat of the pants" flying, the proper X axis translation ΔV for a 360° flyaround in one orbit for the desired flyaround range (as indicated by zero inertial elevation angle rate from the radar or by maintaining the TGT stationary in the COAS), and then simply maintain the Orbiter in inertial attitude hold. This proper rate is shown on the PROX OPS cue card (section 4.3.6). Due to initial MNVR dispersions, cross-coupling effects, orbital mechanics effects, and differential drag, small translation corrections must be made (done manually out the window) during the flyaround to maintain the appropriate range and flyaround rate.

5.2.1.2 Counterclockwise Orbit Rate Flyaround

In certain cases, a CCW rotation flyaround may be executed (fig. 5-6), within a significantly shorter transfer time than using a CW rotation, and there is not an appreciable propellant penalty. This was the case on STS 51-D. In fact, it is cheaper and quicker to go from the V-BAR to the R-BAR by a CCW rotation than a CW rotation. Plume impingement on the target is also reduced because the thruster firings required due to orbital mechanics are toward the target. However, for a given angular displacement (measured clockwise) and transfer time, the CCW rotation requires more propellant. This is due to the fact that (1) the Orbiter must now maintain a pitchdown rate in order to keep the TGT along the $-Z$ COAS LOS (twice orbit rate for a CCW orbit rate flyaround), and (2) the orbital dynamics forces are now operating in conflict with the desired trajectory motion. That is, when the Orbiter is below the TGT and performs the appropriate retrograde X axis translation ΔV for the orbit rate CCW rotation, the resulting trajectory is downward, and considerable translation corrections must be made to force the trajectory back to a constant range, in an upward direction. Most flyarounds are therefore executed in the CW direction.

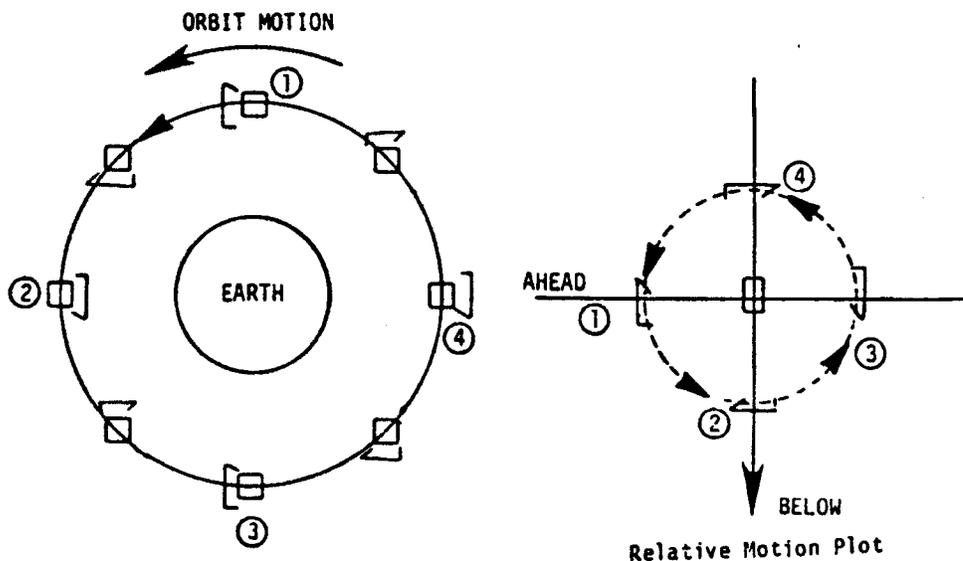


Figure 5-6.- Counterclockwise flyaround.

5.2.2 LVLH out of Plane

A flyaround may also be executed out of plane (in the TGT local horizontal plane). The Orbiter is placed in manual ROT (free drift) PULSE mode in one axis and maintains AUTO attitude hold in the other two axes. For example, if roll is the axis that is to be maintained manually by the crew, pitch and yaw would be in LVLH hold and the Orbiter translations would be performed as required to maintain the proper flyaround rate.

5.2.3 Arbitrary Rate Flyarounds

5.2.3.1 Single Axis

Some situations require a flyaround in a shorter time than ORB rate will allow. In this case, several options are available. One option, called AUTO ROTATION, uses the single-axis AUTO ROT option of UNIV PTG. Although the pilot probably would not mix modes, the task is then to use the THC as required to keep the TGT in the COAS and maintain constant range. This option is limited to pure in-plane flyarounds, performed one axis at a time, since the ROT option fixes the two nonrotating axes inertially. A second option called MANUAL ROTATION can be used in either an inertial (DAP MAN) mode or LVLH (DAP LVLH) mode. In this case, the desired axis of rotation is placed in free (PULSE) and the other two in hold (DISC RATE). The pilot task here is to use the RHC to maintain the desired flyaround rate (pilot would monitor rate on UP and the appropriate rate needle), and then use the THC to accomplish the flyaround. Complicating this technique is the fact that rotation and translation maneuvers cross-couple significantly, which makes it difficult for the pilot to maintain the flyaround rate and still do the required translations. Constant monitoring and correction of rotation rate is required.

5.2.3.2 Multiple-Axis Auto Rotation Maneuver

An arbitrary rate, multiple axes flyaround technique is used primarily for transition to a final approach axis of an inertially stabilized TGT. The approach axis may be pointed in any direction and the TGT may be rotating at a rate other than orbit rate. The flyaround may be an in-plane or an out-of-plane translation, performed manually with the THC and RHC. This is a very challenging task and is not recommended.

This maneuver may be used when the final Orbiter attitude at final approach is known and can be input to the DAP. The Orbiter performs an eigenaxis (i.e., the axis of minimum rotation between two attitudes) rotation maneuver, with manual translations made to keep the TGT centered in the COAS and to maintain a constant range. It is very complex to set up, and therefore manual rotations are generally preferred. However, if done in the proper direction (CW versus CCW for in-plane maneuvers) it can be relatively easy to fly.

5.2.3.3 LVLH (INERTIAL) Orbiter/TGT Alignment Procedure

For an arbitrary (and prerendezvous unknown) TGT attitude, the following procedure was developed for STS 51-I (see fig. 5-7) and was generalized for the contingency book. There are other procedures to accomplish this, but this is very straightforward and is probably the easiest. One axis is corrected at a time. The alternative is to perform a simple inertial approach straight in.

<u>LVLH (INERTIAL) ORBITER/TGT ALIGNMENT</u>	
<u>CAUTION</u>	
	-Z Sense Roll/Yaw (A6U) are the reverse of +X Sense Roll/Yaw (C3)
	Maintain ~0.2 to ~0.3 deg/sec rotation rate
A6U	✓SENSE - -Z ✓DAP TRANS: PULSE/PULSE/PULSE DAP: B/LVLH (MAN)/NORM ✓DAP ROT: DISC/DISC/DISC
	Align ROLL, if reqd DAP ROT: PULSE/DISC/DISC RHC (ROLL) and THC as reqd When Aligned, DAP ROT: DISC/DISC/DISC
	Align PITCH, if reqd DAP ROT: DISC/PULSE/DISC RHC (PITCH) and THC as reqd When Aligned, DAP ROT: DISC/DISC/DISC
	Align YAW, if reqd DAP ROT: DISC/DISC/PULSE RHC (YAW) and THC as reqd When Aligned, DAP ROT: DISC/DISC/DISC
	DAP: B/LVLH (MAN)/VERN, NORM as reqd

Figure 5-7.- Trim Orbiter/TGT alignment.

It must be emphasized that 0.2 deg/s is plenty fast enough as an angle rate, even if it does not look that way out the window. The crew is advised not to go free drift in more than one axis at a time.

5.2.3.4 Manual Rotation Maneuver

A manual rotation maneuver is required when the final necessary Orbiter approach attitude is not known. The pilot gets his cues for starting and stopping the rotational maneuvers either from out-the-window (or CCTV) view of the payload or from checklist procedures. It is performed one axis at a time by repeated application of the ROT techniques described in 5.2.3.

For short-range stationkeeping with a TGT rotating at an arbitrary rate, the Orbiter must manually establish a matched rotation rate (possibly in three axes) while simultaneously translating to stay on the desired TGT axis. While the two previous cases (TGT inertial and TGT LVLH) only required three degrees of manual control (translation), this technique requires six degrees of manual control (ROT and translation). Manual ROT control is required since the AUTO modes require either Orbiter attitude fixed to the inertial or LVLH reference frame (i.e., either zero or orbit rate relative to the inertial frame). This maneuver is tricky since the Orbiter will be rotating about its own c.g., which will be some distance from the nominal grapple position. The best maneuver rate is between 0.2 and 0.3 deg/s. While the vehicle is still controllable at higher rates, fuel usage increases dramatically. In this situation, one may, for instance, prefer to do LVLH stationkeeping on the TGT V-BAR, and perform a rotating grapple.

As already described in section 5.1.2.1, since close-in operations are done at 35 feet, orbital mechanics effects are ignored. Flying is done strictly from a combination of out-the-window and RMS EE CCTV camera views, with delicate eye and hand coordination using the THC and RHC. Attention must also be given to the attitude rates displayed on UNIV PTG (OPS 201) to ensure that the desired rate is achieved and maintained. As in all phases of RNDZ/PROX OPS beginning with the initiation of manual trajectory control, the -Z sense is used exclusively for reasons of consistency and ease of piloting. DAP B/MAN/NORM usually works best.

5.2.4 Auto Targeted Trajectory

This is done (as on STS 51-F) with a general two-impulse maneuver, which requires good onboard NAV for generation of targeting SV's. It is generally required when there is a ΔT constraint in maneuvering from one arbitrary point to another arbitrary point relative to a payload. The NAV targeting maneuver execute logic is used instead of the thrust monitor function. Certain orbit targeting I-loads need to be "tuned" for operations at PROX OPS ranges (see discussion in section 3.5.4.). The automated rotation maneuvering may be used as a backup in the event of RR failure. However, this must be carefully planned preflight, as on STS 51-F (see discussion in appendix A).

5.2.5 LOS Rate Techniques

The Orbiter-to-TGT radar LOS rate tends to jitter due to beam wandering, but when smoothed (either mentally, via some TGT characteristic, or via some as-

yet undeveloped sensor), this parameter may be able to provide a valuable cue for PROX OPS piloting, especially for performing in-plane MNVR's in the vicinity of the V-BAR. The following discussion deals with a candidate procedure not yet validated or flown.

The inertial LOS rates are displayed on the cross pointer as EL and AZ rates on the A2 panel (fig. 3-20) and on SPEC 33 (REL NAV) (fig. 3-31) as ω_P (for EL rate) and ω_R (for AZ rate) on the RR column. These rates specify how much the LOS, a line from the Ku-band radar antenna to the TGT, is moving with respect to the inertial space, referenced on the RR EL/AZ coordinate system.

First, consider the case of a transition to the V-BAR, as is done at the final portion of a rendezvous maneuver (fig. 5-8). The Orbiter achieves inertial stabilization by selection of DAP MAN/DISC, maintaining the TGT in the COAS FOV by THC inputs. Evidently, for such a transition, the RR EL LOS rate is going to be about zero, depending on the THC corrections required in the +X or -X direction to maintain the TGT in the COAS. The LOS to the TGT, then, is going to rotate with respect to the LVLH TGT centered frame at the orbital rate, that is about 4 deg/min, or 1.16 mrad/sec (in what follows, this value is rounded to 1.1 mrad/sec):

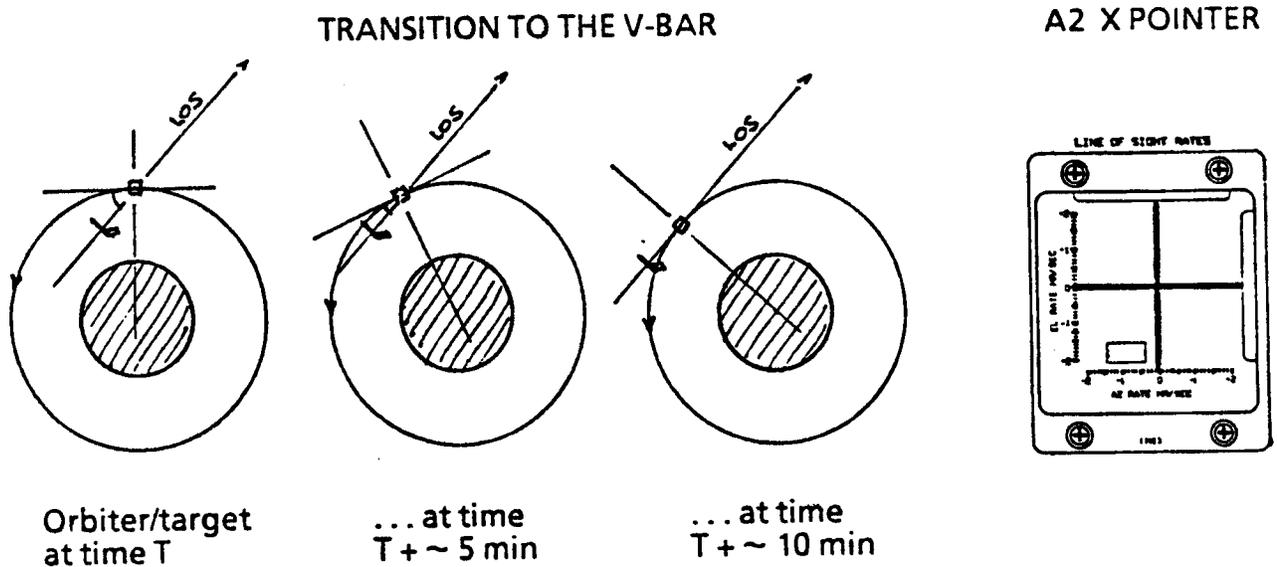


Figure 5-8.- Transition to the V-BAR.

When on the V-BAR (fig. 5-9), to stay there, the Orbiter must null its upward motion. The crewman uses the THC in the -X direction, preferably in the pulse mode, to take away about as many ft/s of +X motion as range to the TGT is in kft (1 ft/s for 1000 ft range, for instance). Previously, of course, the crew must have set up the UNIV PTG to have the -X body vector tracking the center of the Earth upon reaching the V-BAR, at which point

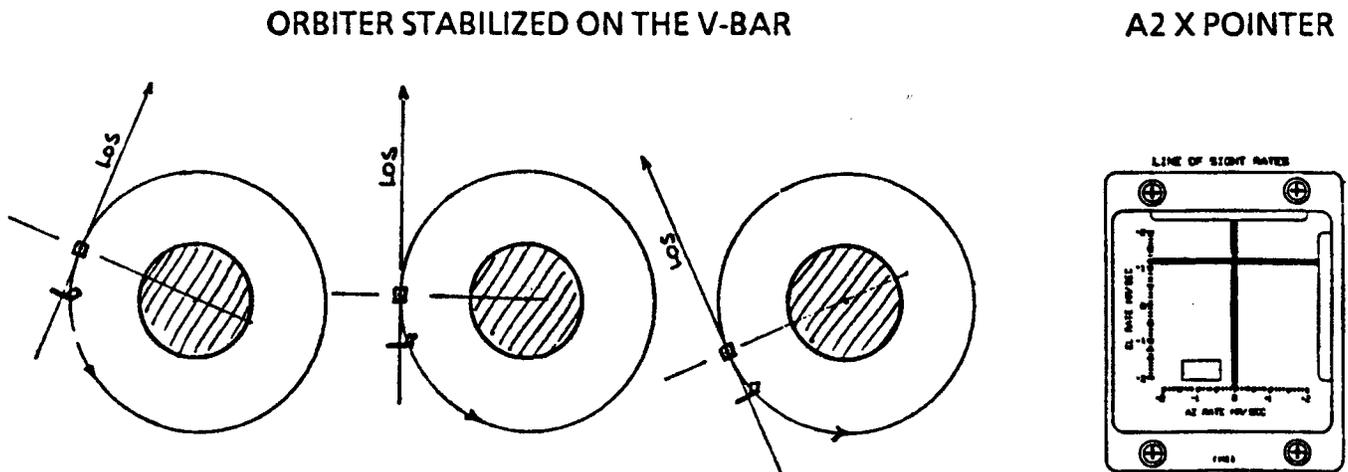


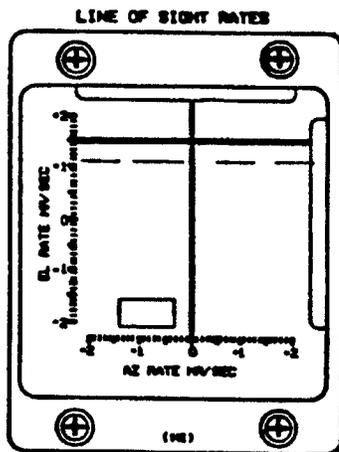
Figure 5-9.- Orbiter stabilized on the V-BAR.

select DAP AUTO. The -X translation MNVR that is performed in order to brake on the V-BAR will cause the EL LOS rate to increase. When it shows 1.1 mrad/sec, or thereabouts, the Orbiter is established on the V-BAR. The LOS, rotating with respect to the inertial space at the orbital rate of 1.1 mrad/sec, will then evidently remain fixed with respect to the TGT centered LVLH frame.

The EL LOS rate is not expected to tell anything about whether the Orbiter is approaching the TGT, or going away from it, or maintaining range. But over a period of time a closing R-DOT will cause a fall below the V-BAR, and the EL LOS rate will become higher than 1.1 mrad/sec. An opening R-DOT will, on the contrary, go above the V-BAR, and EL LOS rate will go below 1.1 mrad/sec (see fig. 5-10).

Instead of using the A2 panel crosspointer, the crew can, of course, use ω_P on the REL NAV display. A good value indicating proper stabilization on the V-BAR is 1.1. For any value above that, the Orbiter is going down. For a value below that, the Orbiter is going up.

YOU ARE COMING DOWN, BELOW
THE V-BAR



YOU ARE GOING UP, ABOVE
THE V-BAR

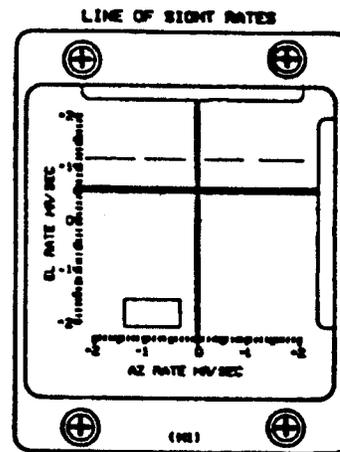


Figure 5-10.- Angle rates versus V-BAR stability

EL LOS rate is also useful to consider in a V-BAR approach (see fig. 5-11). After proper stabilization on the V-BAR, the crew establishes the desired closing range rate with the THC, and initiates a +X translation of such an amplitude as to reduce the EL LOS rate from 1.1 to about 0.7 or 0.8 mrad/sec. The crew knows then that it is getting a small amplitude hop above the V-BAR. EL rate will slowly increase. When the Orbiter gets again 1.1 mrad/sec, the tangent of the trajectory in the LVLH frame is passing through the TGT, but the Orbiter still is above the V-BAR. Whenever the crew visually ascertains that it is again on the V-BAR, they translate in +X again to bring its EL rate below 1.1 mrad/sec. The crew continues that way until it is at the stationkeeping range.

V-BAR APPROACH

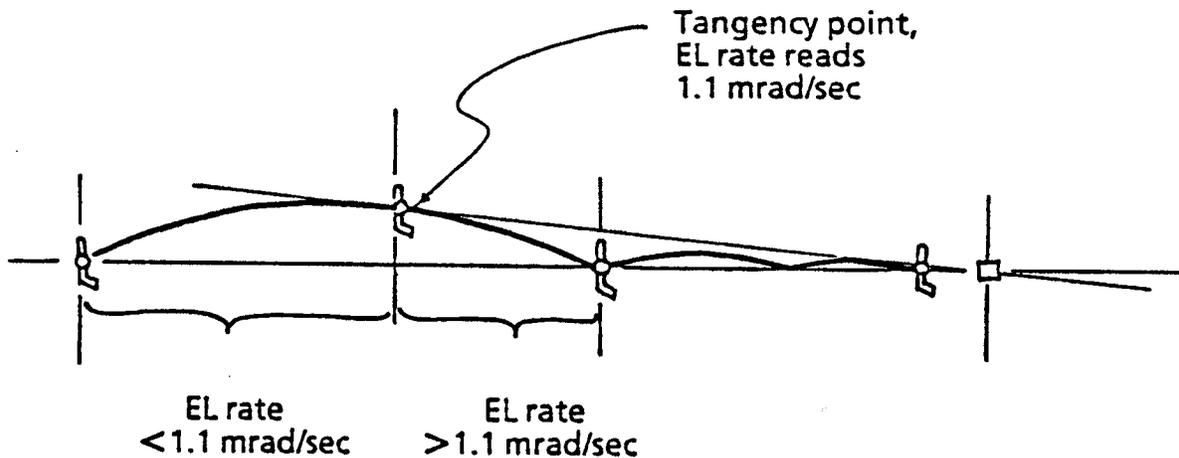


Figure 5-11.- Angle rates versus V-BAR approach

5.3 FINAL APPROACH

The final approach phase includes various braking and approach techniques.

5.3.1 Braking Techniques

The braking segments typically occur near TGT intercept and reduce relative velocity to near zero. The technique to be used for braking is greatly dependent upon the approach trajectory. For example, the technique used for a direct RNDZ intercept must reduce a large relative velocity, whereas the technique used just prior to capture must null only a small closing velocity. It is not the intent of this section to define the possible braking approach profiles, but to describe the thrusting techniques by which the Orbiter can achieve a stabilized relative position. Four techniques will be discussed, three involving the use of the PRCS and one (already discussed in section 2.4.3) using more dynamic orbital mechanics effects.

5.3.1.1 Normal Z-Axis Mode Braking

The normal Z-axis braking technique uses the up-firing PRCS thrusters to achieve a braking force directed in the +Z Orbiter body direction. This technique would be used in the case where the Orbiter -Z axis was pointed along the LOS to the TGT (fig. 5-12). Because the thrusters firing along the -Z axis provide the braking force, this technique results in the greatest amount of PRCS plume impingement on the TGT. Either the TGT must be insensitive to plume

contamination/overpressure, or braking must occur outside of a contamination/overpressure sphere where plume effects are negligible. However, this orientation does allow crew monitoring of the TGT through the overhead window and use of the RR.

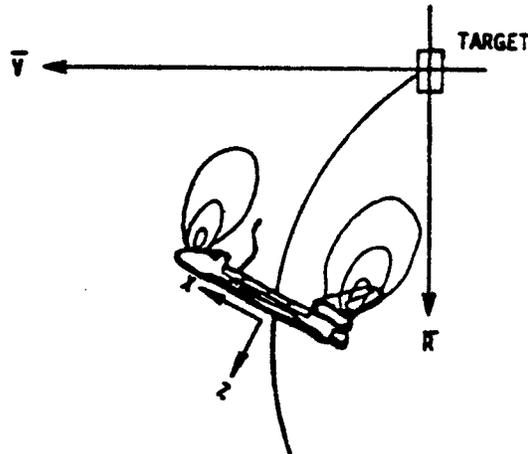


Figure 5-12.- Normal Z axis braking.

The braking force would normally be applied to achieve a range/range rate profile that is optimized to account for Orbiter PRCS acceleration, trajectory dispersions, and TGT sensitivity to PRCS plume. The RNDZ radar is normally used to determine actual range/range rate. Control of the relative velocity normal to the LOS during braking is accomplished by PRCS thrusting to achieve a specified inertial LOS rate. This rate is read directly from the radar LOS rate display (panel A2) or observed by monitoring TGT drift in the COAS reticle.

5.3.1.2 Low Z Mode Braking

The low Z-axis mode braking technique is the standard technique used (as a modification to normal Z axis mode braking) to reduce the PRCS plume in the Orbiter -Z direction. As described in section 3.2.4, the technique uses the cant of the aft firing thrusters and the scarfing of the forward firing thrusters to produce a resultant force in the +Z direction (fig. 5-13). The $\pm X$ axis firing is controlled by the DAP to produce a near zero force in the X axis direction. The propellant penalty (12 times NORM Z for same $-\Delta V$) is minimized by using the low Z axis braking mode only in the interval from the boundary of the PRCS plume sphere of influence to the close-in point over the PLB, where the TGT is "shadowed" by Orbiter structure, and reducing the total braking ΔV inside the sphere to the smallest possible value.

Because of severe cross-coupling effects (see section 3.8.1.3), Y-axis translations induce higher closing rates, requiring expensive braking maneuvers. Consequently such translations should be avoided in this mode.

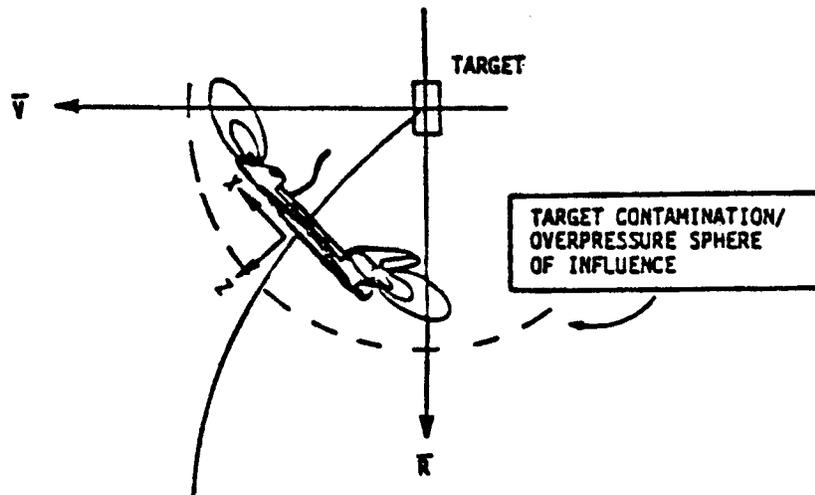


Figure 5-13.- Low Z axis braking.

5.3.1.3 X-Axis Mode Braking

The +X or -X axis thrusters could provide the braking force; however, operational constraints would normally preclude their usage. The +X axis braking mode (nose first) would not be desirable since it requires almost totally forward-pod propellant usage, which should be minimized. The -X (tail first) braking mode has the advantage that it minimizes forward-pod propellant usage; however, TGT visibility (crew and radar) would not be possible when thrusting along the TGT LOS (fig. 5-14). This technique of braking is not recommended for use due to the limited visual capabilities and plume concerns. Another concern with this type of braking is the safety issue involved with the clearance between the Orbiter tail and the TGT.

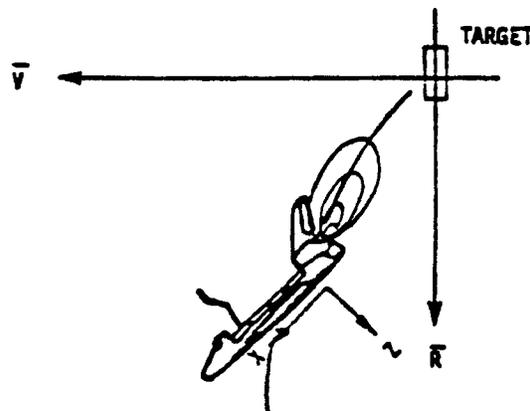


Figure 5-14.- +X axis braking.

5.3.1.4 Orbital Mechanics Effects Braking

Although not strictly a braking technique, orbital mechanics effects can provide a small separation force (see section 2.4.3). The relative position of the Orbiter with respect to the TGT can result in range opening or closing tendencies during PROX OPS.

For example, a TGT approach along R-BAR (from above or below the TGT) will result in a braking force which is a function of the differential altitude or range to the TGT (fig. 5-15). The greater the range, the greater the constantly acting separation force. The technique for establishing an approach trajectory to produce this R-BAR braking force is discussed in section 5.3.2.3. Compare the sizes of that "thrust" to RCS effects: two -X jets cross-couple into a momentary 240-pound +Z thrust; two +X jets cross-couple into a momentary 300-pound +Z thrust. In practice, the RCS cross-coupling dominates the small orbital mechanics forces for ranges less than several hundred feet. Outside that range, the forces are significant when one notes that they are constantly acting, whereas Orbiter jets are only sporadically fired.

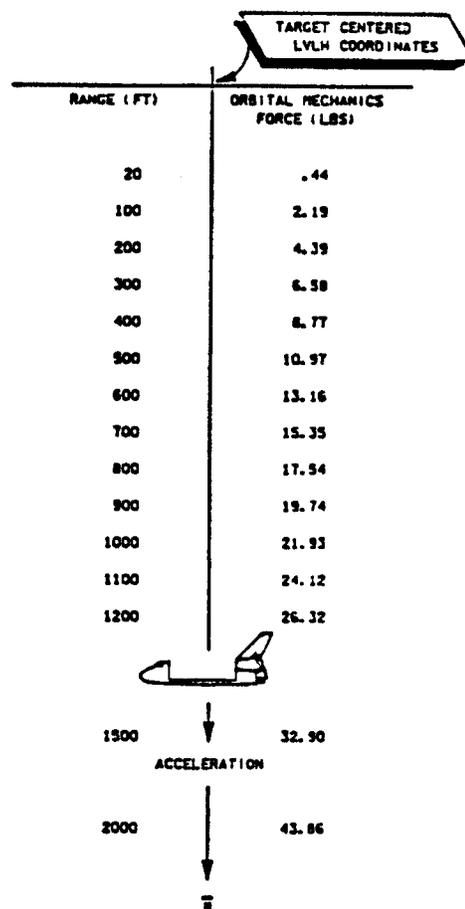


Figure 5-15.- Orbital mechanics forces during an R-BAR approach.

5.3.2 Final Approach Techniques

The selection of a final approach technique is greatly dependent upon the TGT sensitivity to Orbiter thruster plume impingement. Several techniques have been evaluated and shown to be operationally feasible. Each requires a different amount of ΔV to be nulled by thrusting in the direction of the TGT using one of the braking methods discussed above.

The approach techniques are illustrated in figure 5-16.

- Direct approach - used on rendezvous intercept trajectory with relatively large ΔV to be nulled (not typically used in the STS program).
- V-BAR approach - used for approach from ahead (+V-BAR) or behind (-V-BAR) with relatively small ΔV to be nulled.
- R-BAR approach - used for approach from above (-R-BAR) or below (+R-BAR) with theoretically zero ΔV to be nulled.
- Inertial approach - used for approach to an inertially stabilized TGT which is rotating relative to the LVLH reference frame.

Current analysis, simulations, and actual flight experience have led to the choice of V-BAR as the preferred approach technique. However, the flight procedures techniques associated with all these approaches are discussed in detail below.

5.3.2.1 Direct Approach

The direct approach can also be described as rendezvous intercept to a close-in stationkeeping position (fig. 5-17). The magnitude and direction of the intercept ΔV to be nulled are dictated by the maneuver targeting which produced an intercept trajectory. The intercept ΔV is gradually reduced by a series of braking thrusts that follow the low range/range rate profile as shown. Throughout the approach, the Orbiter is either in inertial (preferred) or LVLH attitude hold with the TGT centered in the COAS. The crew applies thrust normal to the LOS as needed to null off-nominal LOS rates. (Intercept targeting can be designed to produce either zero or ORB rate inertial LOS rates during the braking phase, although the advantage of the latter has never been demonstrated.) The radar would normally be used to determine range and LOS angle rate data.

The most efficient braking method would be the normal Z-axis mode since it provides maximum translation control authority. The low Z-axis mode can be used to significantly reduce PRCS plume effects on the TGT during the last few range/range rate gates; however, the substantial propellant consumption penalty must be considered in using this technique.

This technique has not been used since the Skylab program, when plume impingement concerns were much less than today (due to the small mass of the Apollo and the large size and mass of Skylab), and when the robust in-line docking mechanisms provided safety margins to closing rate dispersions.

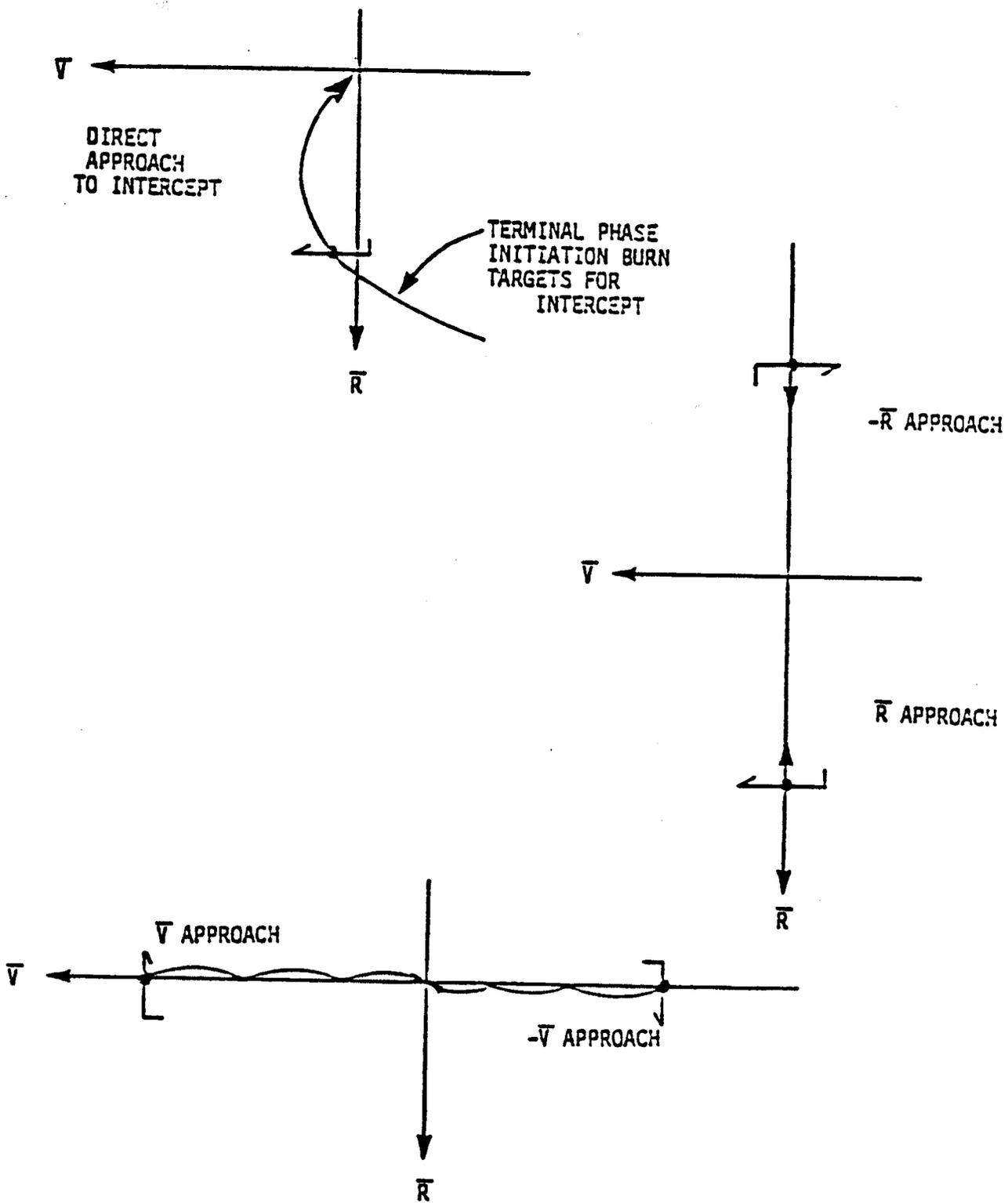


Figure 5-16.- Typical final approach techniques.

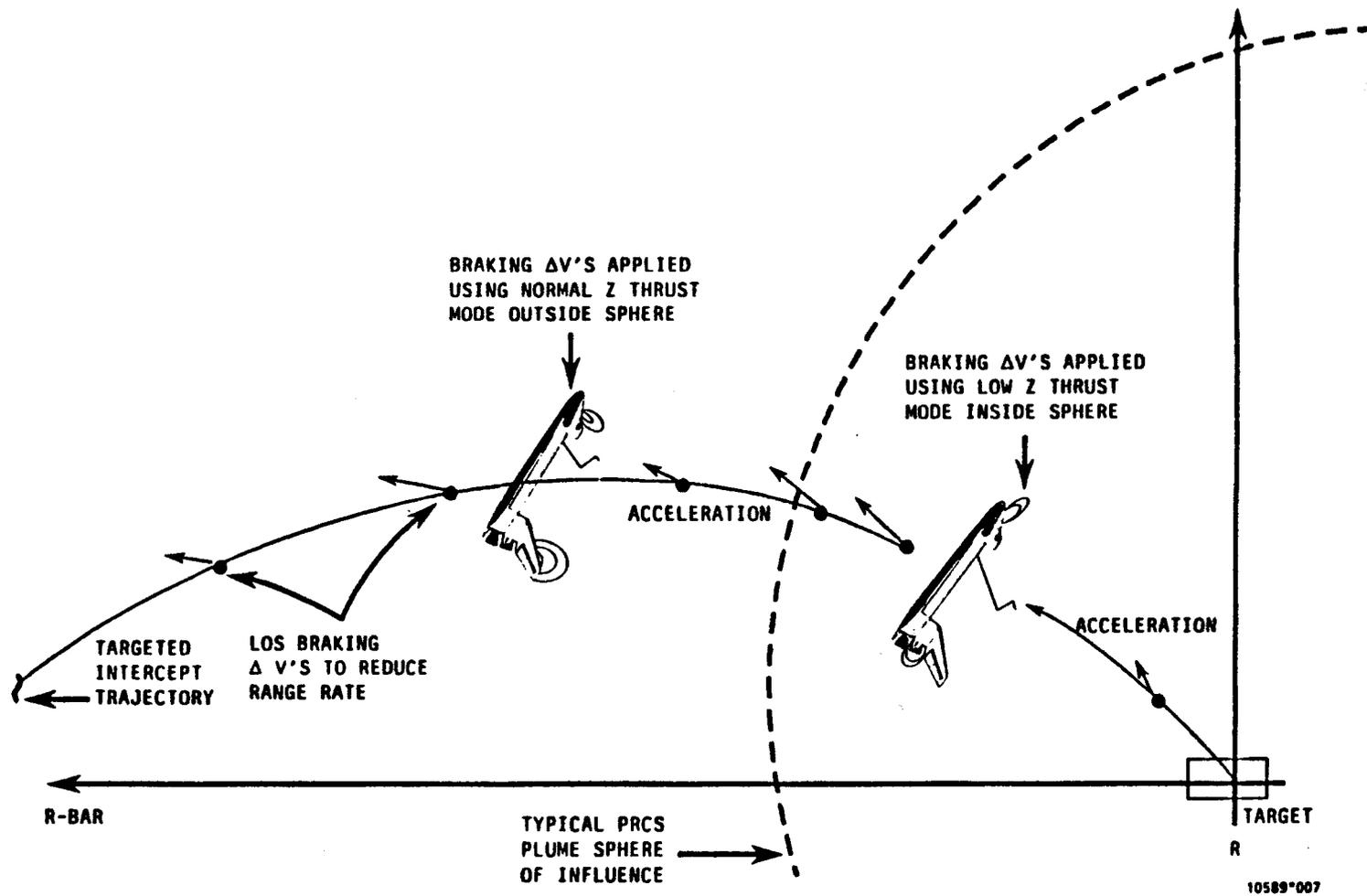


Figure 5-17.- Direct approach to close-in stationkeeping.

5.3.2.2 V-BAR Approach

The V-BAR approach technique assumes medium-range stationkeeping on V-BAR has been established ahead of the TGT (fig. 5-18); no -V-BAR (trailing the TGT) technique has ever been attractive. The approach is initiated with a ΔV directed toward the TGT (and with some +X from cross-coupling). Orbital mechanics effects (section 2.4.3.3) tend to slow the approach, making the Orbiter fall below the V-BAR and then reverse motion away from the TGT. Therefore, to maintain a closing rate for a +V-BAR approach, the crew must thrust up (normal to the TGT LOS) at each V-BAR crossing to maintain the Orbiter above the V-BAR axis. This then produces a series of trajectory hops until capture distance is achieved. The magnitude of the initial and intermediate ΔV 's is a function of range and magnitude of the NLOS rates.

During the approach, the Orbiter attitude is being automatically pitched at orbit rate (using a -X to Earth attitude hold mode), with the X-, Z-body axis continuously aligned with the R-BAR and V-BAR axes, respectively. The crew monitors the TGT drift in the COAS (or CCTV aligned along -Z) and applies the X-axis translations as required.

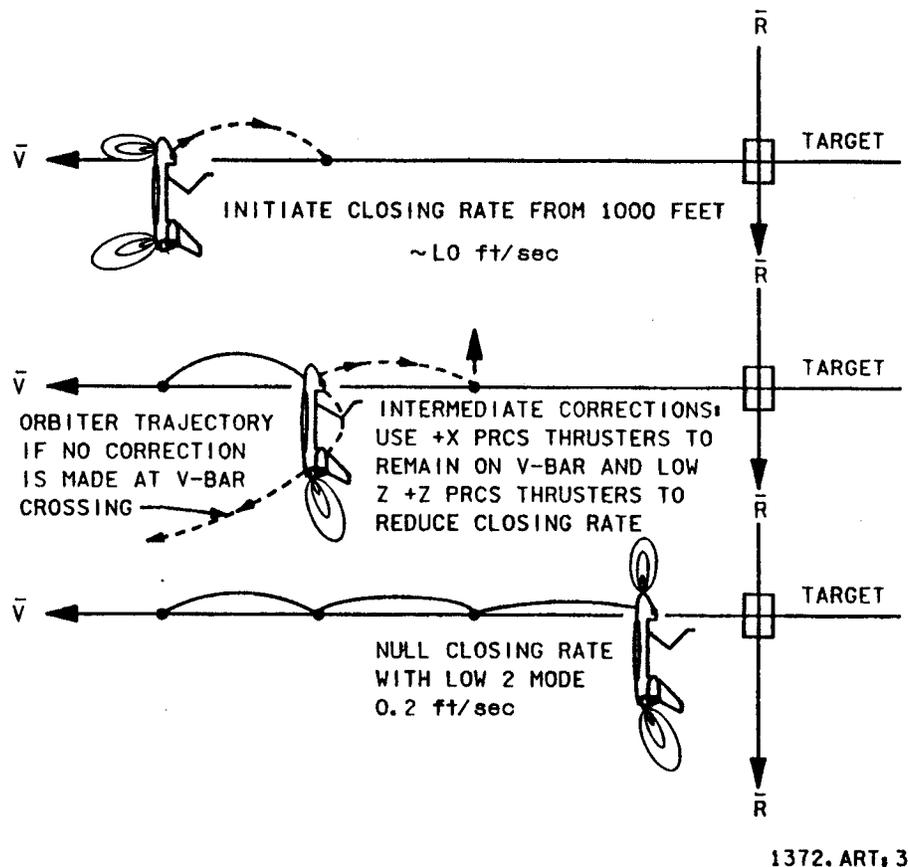


Figure 5-18.- V-BAR approach.

Predetermined braking gates will be used to null the closing rate (established to initiate the approach) prior to RMS grapple. This closing rate should be gradually nulled, with the NORM Z/low Z braking mode as required, to minimize PRCS plume effects on the TGT.

The +V-BAR approach procedures and rationale are described in detail at the end of the RNDZ in chapter 4, beginning at section 4.1.63 through section 4.1.71.

The +V-BAR approach is the preferred choice for a number of operational reasons. Current RNDZ methods schedule optical tracking so that V-BAR arrival occurs at noon. Also, +V-BAR arrival allows use of Orbiter attitude already held during manual phase RNDZ. For stationkeeping, +V-BAR also facilitates the quickest visual TGT acquisition at sunrise.

5.3.2.3 R-BAR Approach

The R-BAR approach utilizes both PRCS thruster cross-coupling and orbital mechanics effects to provide the braking force. This technique minimizes PRCS thrusting toward the TGT (practically zero). In practical application, however, the crew applies a series of small thrusts to "walk" up the radius vector (fig. 5-19). This piecemeal approach allows correction for errors made while initially determining and applying the proper closing rate.

The theoretical R-BAR technique requires the use of an analytically derived R-BAR approach profile chart (fig. 5-20), or handheld calculator program (currently nonexistent). Sample data has been plotted on the chart (dashed line) to show a typical approach where the initial closing rate at 1000 feet (R-DOT = 1.5 ft/s) was sized to take the Orbiter to 600 feet; the next correction applied at 670 feet (R-DOT = 1.0 ft/s) was sized to take the Orbiter to 400 feet; the next correction applied at 500 feet. (R-DOT = 0.7 ft/s) was sized to take the Orbiter to 300 feet, and so forth. Range and range rate measurements must, of necessity, be very accurate at short ranges; hence, radar data is recommended.

Because of the sensitivity of the R-BAR technique to range/range rate errors, a supplemental PRCS braking method may have to be used. If the R-DOT at the retrieval position exceeds the limit for RMS capture, the low Z axis braking mode is recommended to null R-DOT without producing direct PRCS plume impingement on the TGT.

This technique has not been operationally used to date. However, -R-BAR approach techniques have been developed in the SES for planned use during the LDEF retrieval mission and were documented in the original STS 51-D FDF.

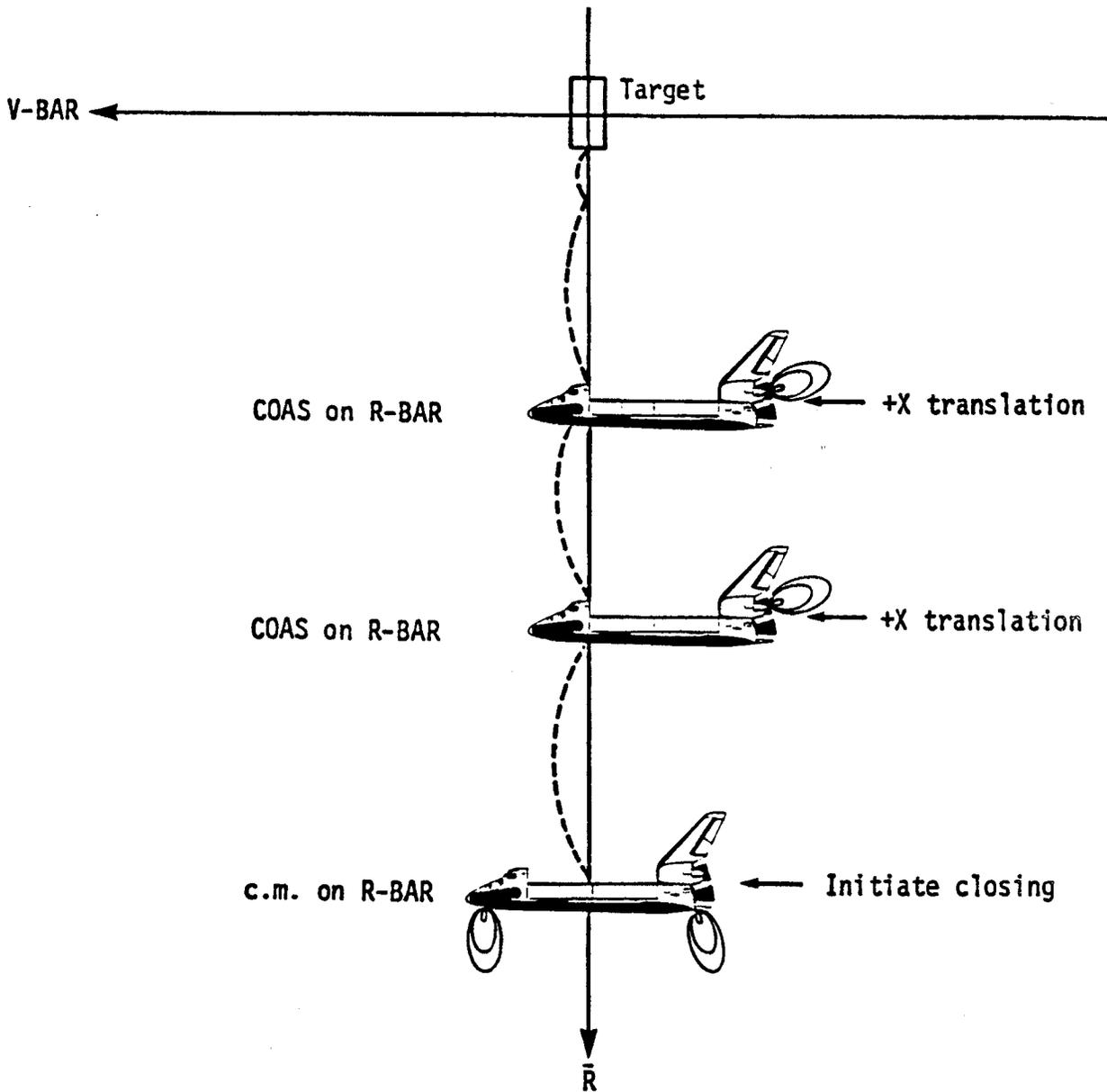


Figure 5-19.- Generic R-BAR approach technique.

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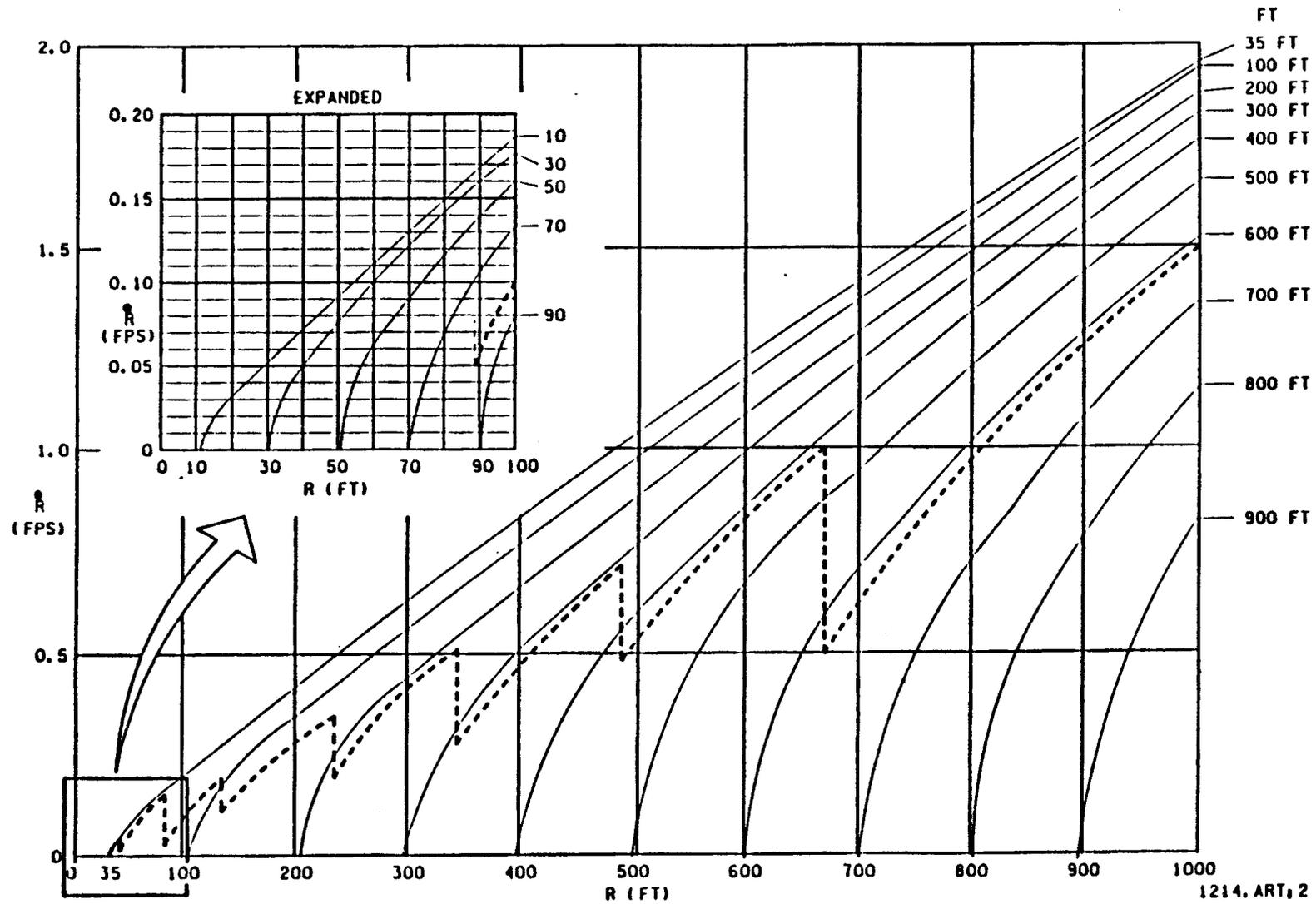


Figure 5-20.- Typical R-BAR approach profile.

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Rendezvous and manual phase procedures are identical to those described in section 4, up through establishment of inertial LOS rates (section 4.1.61); braking gates are the same as those described in section 4.1.64.

Due to contamination concerns for LDEF, DAP low Z is selected at a range of 1000 ft.

The next stage is to configure for final approach, and this follows closely the standard "Reconfigure RR" (section 4.1.62), "Configure UNIV PTG for V-BAR" and "Configure DAP for PROX OPS" (section 4.1.66), with one exception. The BODY VECT ID on UP is selected as +3 (the -Z axis) if the -R-BAR approach is intended (otherwise it is +2, as usual).

The approach profile is illustrated in figure 5-21.

The "400 FT TRANSITION" occurs at R = 400 feet, which nominally occurs at the V-BAR crossing. The R-DOT is nulled while the Orbiter is in inertial hold, and an inertial flyaround begins as the THC is commanded as required to maintain TGT in top of COAS. The 90° flyaround should take about 22

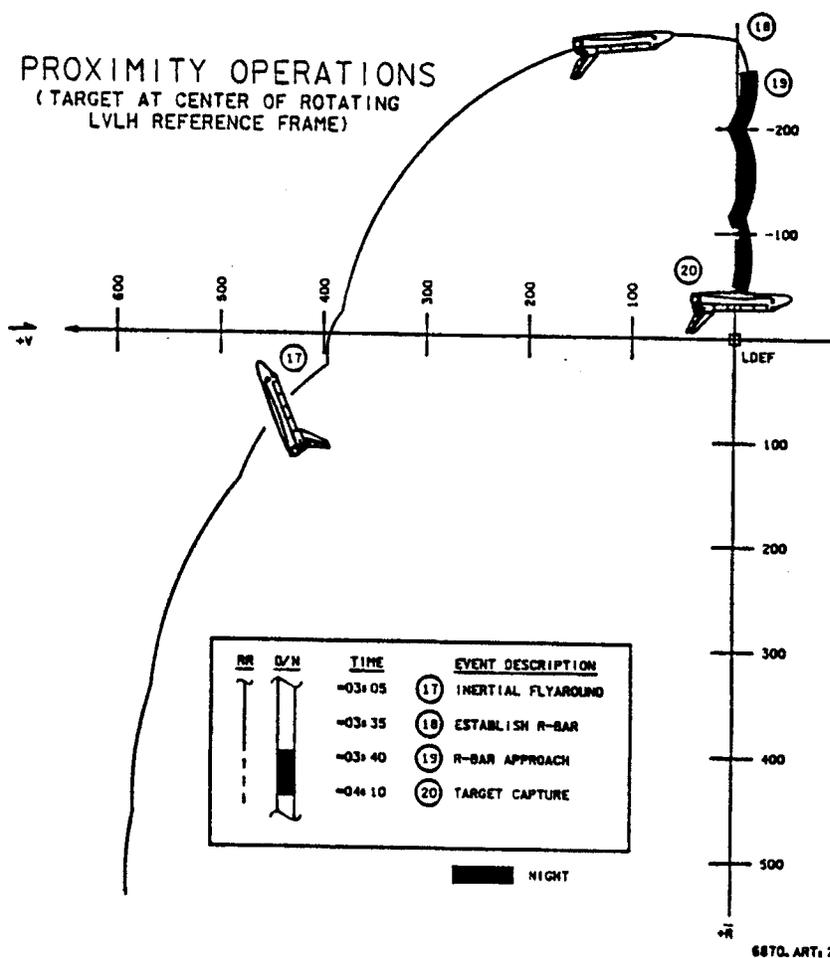


Figure 5-21.- LDEF R-BAR approach.

Once the TGT is grappled (about at sunrise), adjust attitude as follows with maneuver to -ZLV, -XVV, as shown in figure 5-23 checklist.

CDR	When LDEF in HOVER position; BRAKES - ON. <u>MNVR TO -ZLV, -XVV</u>
	Config DAP B to B8
	<u>GNC UNIV PTG</u>
CRT	✓TGT ID +2 ✓BODY VECT +3 (-Z) OM +0 TRK - ITEM 19 EXEC (CUR - *)
A6U	DAP: B/AUTO/VERN
	When attitude MNVR complete.
CDR	✓DAP ROT: PULSE/PULSE/PULSE DAP: B/MAN/VERN
MS1	<u>LDEF BERTH</u>

Figure 5-23.- Post-grapple maneuvers

5.3.2.4 Inertial Approach

The inertial approach technique is required for payloads which are inertially stabilized in at least two axes. The technique breaks down into two phases: a constant range flyaround to the appropriate payload approach axis and the final approach to RMS grapple range. The two phases could be combined.

The flyaround phase is performed at some range (such as 35 feet) close enough to allow CCTV ranging and to keep the target in the plume shadow (minimizing plume effects). Two types of flyaround techniques are utilized, depending on whether the target attitude, relative to the Orbiter reference frame, is known or not. If the TGT attitude is known, the multiaxis Auto rotation maneuver flyaround technique, described in section 5.2.3.2, would be used. If the TGT attitude is unknown, one of the manual rotation maneuver techniques, described in section 5.2.3 would be used. The multi-axis rotation maneuver technique is obviously the more efficient, as it rotates the Orbiter about the optimum axis (eigenaxis), thereby minimizing the translation corrections required to achieve the payload final approach axis. Manual rates up to 0.2 to 0.3 deg/s are utilized.

Upon arrival on the target final approach axis, the final approach phase begins. The Orbiter is maintained in inertial attitude hold and a closing rate of about 0.2 ft/s is initiated toward the target. During the approach, NLOS rates, as detected in the COAS, are nulled by THC deflections. Upon arrival at the desired grapple range, all relative rates are nulled and capture operations commence.

5.4 SEPARATION

Separation is a PROX OPS task involving the execution of a translation maneuver or sequence of translation maneuvers, which result in an opening (separation) rate between two orbiting satellites. Either or both of the satellites may take an active role in performing these maneuvers. Since one of the two satellites is usually a PL, originally located (berthed) in the Orbiter PL bay, the term "PL" is normally used (vs. TGT) in separation techniques discussions.

The separation problem differs significantly from other phases of PROX OPS. These differences can be summarized as items which either simplify (advantage) or complicate (disadvantage) this task relative to the other PROX OPS tasks.

In some cases, only appendages of a PL are to be jettisoned so that the main body can be returned to Earth. Since the PL may still be on the RMS, the Orbiter would not be able to perform an active separation maneuver. However, the Orbiter would prefer to perform an attitude maneuver such that the appendages would separate in the most advantageous direction to avoid both near-term and long-term recontact. Here, preflight analysis of relative drag characteristics and jettison ΔV is crucial.

Advantages:

- The problem begins with a well known REL SV.
- Orbiter burns and attitude maneuvers can be expected to follow a canned sequence, making propellant consumption predictable.
- Confidence in the separation trajectory reduces crew monitoring requirements. (Dispersions have not yet had a chance to build up.)

Disadvantages:

- Many PL's have tight deploy attitude and rate error requirements.
- Some PL's have upper stage boosters which pose a potential hazard to the Orbiter.
- For RMS deployed PL's, checkout may not be completed until after deploy, requiring an Orbiter recapture capability, sometimes for several hours or days. This may require contingency RNDZ planning.

- There may be relatively low confidence in PL control system characteristics.

A review of these points indicates that flying the Orbiter is a simpler task for separation than it is for the other PROX OPS tasks. On the other hand, the frequency of deploy missions versus retrieval missions points out the importance of an efficient solution to the separation problem.

In the design of a separation sequence, many factors must be considered, but five general concerns stand out:

- Orbiter/PL (or appendage) recontact, both short term and long term.
- Crew visibility of the PL.
- Orbiter plume impingement on the PL, both RCS and OMS.
- PL plume impingement on the Orbiter, particularly for PL's on an upper stage such as the PAM or IUS.
- Crew safety relative to hazardous PL control system performance.

For many PL's, these may be somewhat contradictory and require a relative weighing on a case by case basis.

5.4.1 Nominal

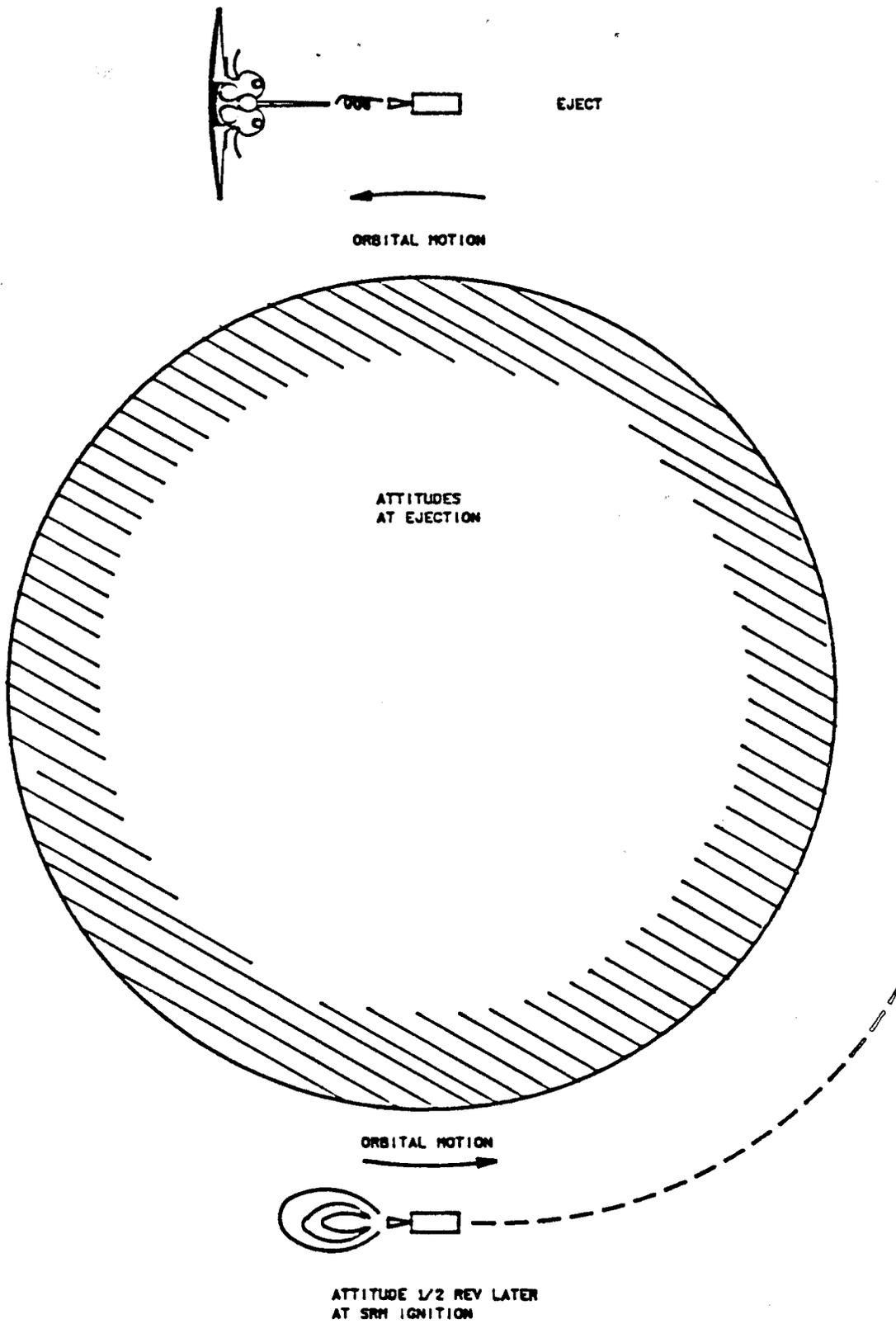
PL's may be nominally deployed by spring ejection or RMS release.

5.4.1.1 Spring Ejection (PAM)

Since most deployments involve spring ejection, this clearly calls for a simple, standardized, efficient separation sequence which minimizes training requirements. This will result in a sequence which may not necessarily be optimized for a specific mission, but will reduce mission preparation effort.

For payload assist modules (PAM-D's) deployment, there are two important booster characteristics which drive separation sequence design. First, attitude control is accomplished solely by spinning the upper stage at a high rate, e.g., 50 rpm. This fixes the Orbiter attitude at deployment in two axes, leaving the third free to rotate about the deploy LOS. Second, this is a solid rocket booster, which for the PAM-D has a built-in 45-minute "fuse" which cannot be safed postdeploy.

To further constrain the deploy situation, in general the PAM-D will burn very nearly posigrade, with an out-of-plane component determined by PL weight and orbital inclination. Thus, 45 minutes (1/2 rev) earlier, the PAM-D must usually be ejected retrograde, as indicated in figure 5-24.



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Figure 5-24.- PAM/Orbiter ejection attitude.

The ejection velocity is on the order of 2.4 to 2.8 ft/s (1.5 to 2.0 ft/s for PAM-D-II's), resulting in a relative motion trajectory as shown in figure 5-25 with the coordinate system rotating at ORB rate and centered on the PL. From the figure it can be seen that in 1/2 REV, at SRM ignition, the Orbiter will be above and behind the PAM-D. Given this initial data, analysis was conducted to determine what Orbiter separation was required to ensure a lifetime TPS erosion of < 10 percent based on design lifetime of 100 STS missions. (This number is based on MDTSCO Design Note No. 1.4-3-016.) Using a manifest which at that time indicated a total of 135 upper-stage firings over the first 100 STS flights, a criteria of 0.074 percent erosion per flight was established. If no additional ΔV is added by the Orbiter, the separation resulting from the spring ejection alone will result in a plume impingement on the Orbiter TPS of about eight times the accepted level. Although this is not a safety problem for one flight, it is clear that in general an Orbiter burn is required to increase separation distance.

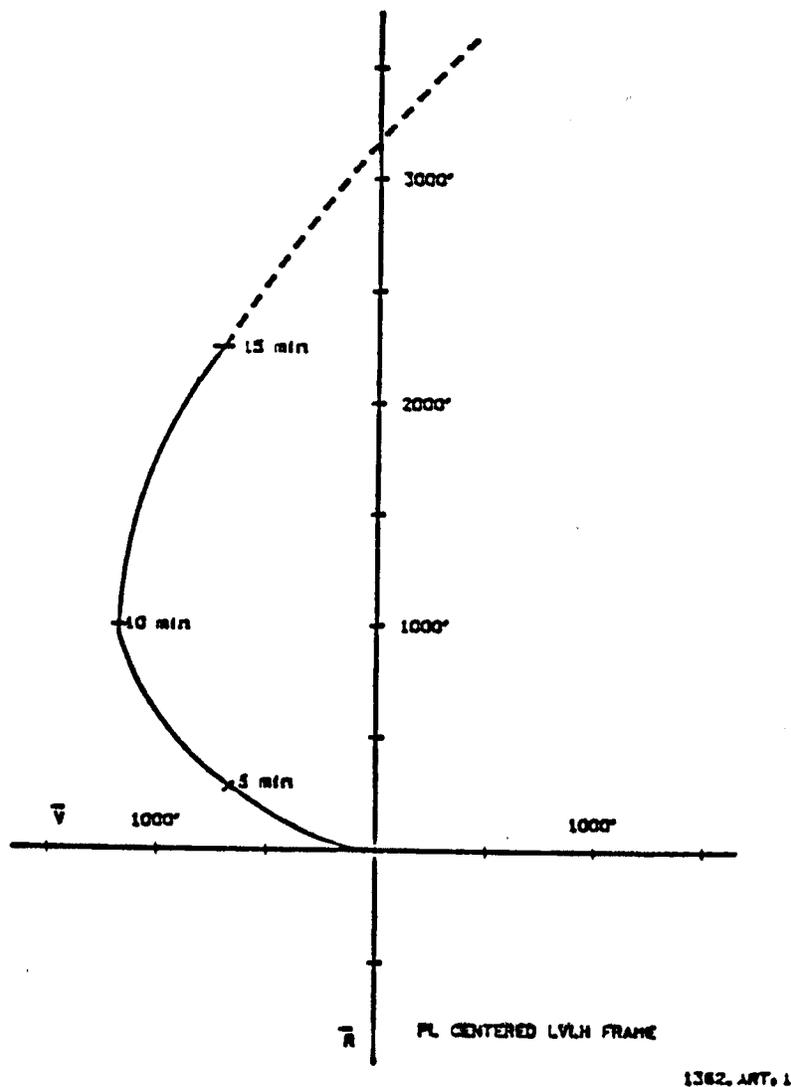


Figure 5-25.- Orbiter/PAM-D separation trajectory (due to ejection ΔV only).

To achieve maximum separation at SRM ignition, the Orbiter OMS burn should be scheduled as early as possible after deploy, although about 10 minutes are required to get ready for the burn. Estimating then that SRM ignition will occur about 35 minutes after the OMS burn, it can be shown that the plume impingement on the Orbiter can be minimized if the upper stage thrust vector is about 15° above posigrade. With this choice made, it is then possible to determine a time for the OMS burn, based on acceptable Orbiter plume impingement on the TGT. If the burn is delayed until deploy +15 minutes, the plume overpressure on the PL will be $< 10^{-4}$ lb/ft², which was chosen as an acceptable level (fig. 5-26). Coincidentally, due to the 16° cant of the OMS engines, which places the thrust vector through the Orbiter c.g., it is possible to do the burn in -ZLV, wings level. This allows for a convenient manual "out the window" backup burn.

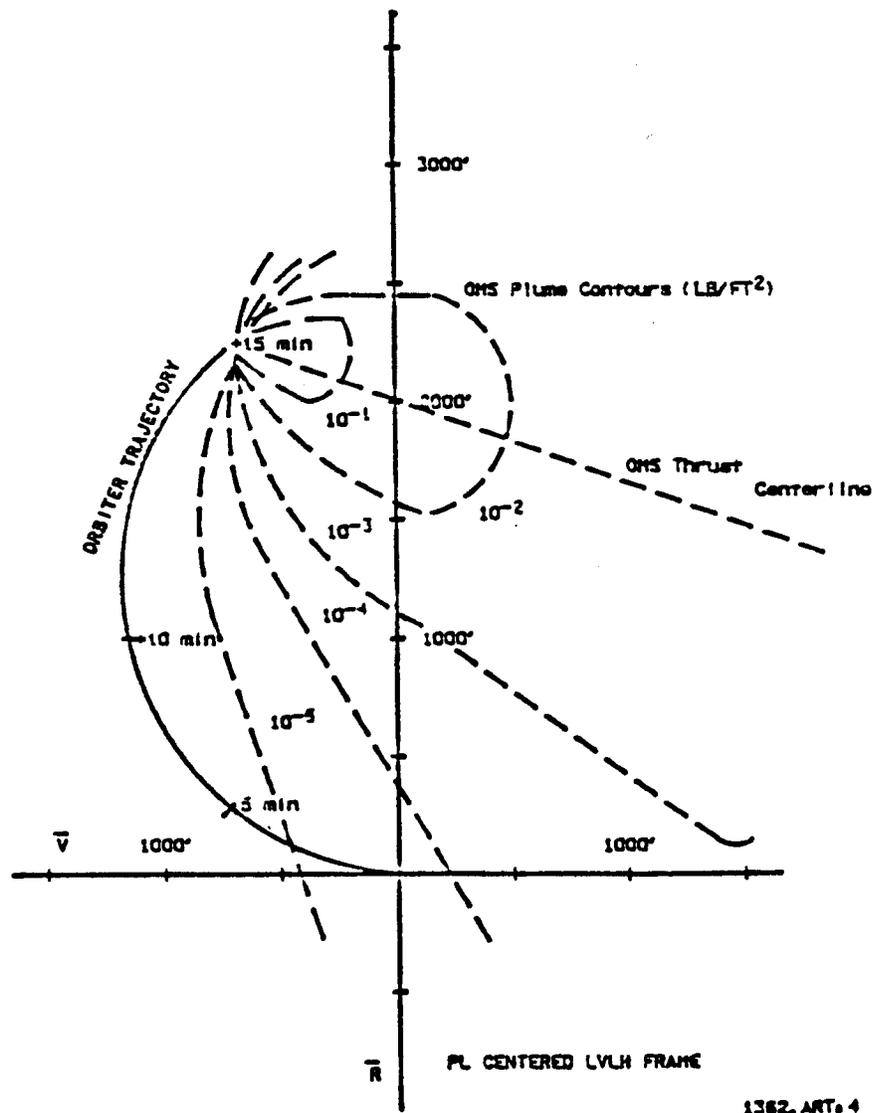
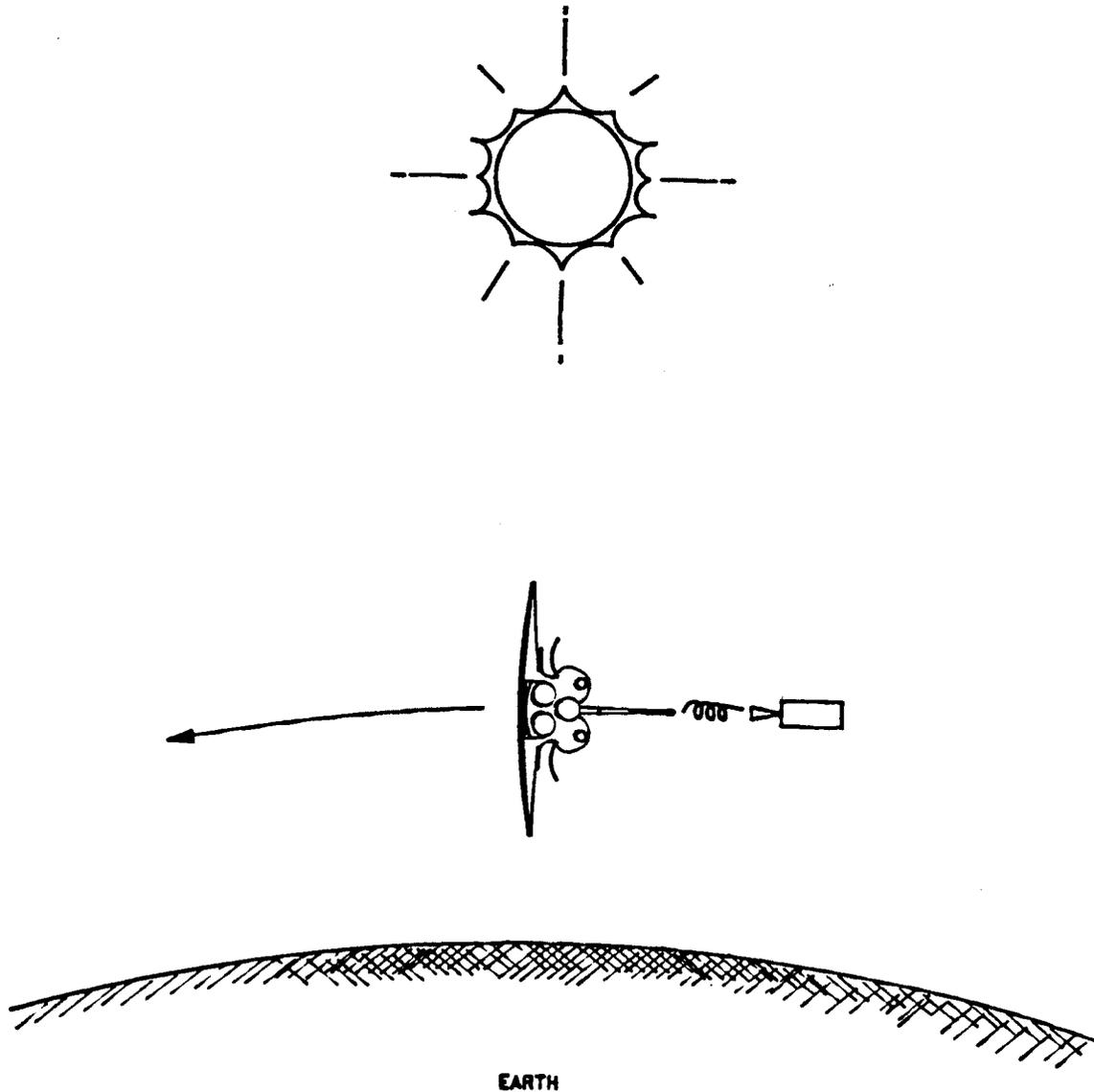


Figure 5-26.- OMS plume on PAM-D at SEP burn initiate.

Continuing to work backwards to deploy, we can now constrain the third Orbiter degree of freedom to minimize the maneuver to the OMS burn attitude, resulting in a -XLV deploy attitude. However, since the PAM-D must be ejected near orbit noon (or midnight) to meet thermal constraints, this may, for some beta angles, violate the groundrule of no Sun within $\pm 20^\circ$ of the PL LOS during deploy and SEP. To solve this problem, the Orbiter is rotated such that the X-axis is out of plane at deploy, as shown in figure 5-27.



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Figure 5-27.- Orbiter attitude at PAM ejection.

It should also be pointed out that this entire sequence was designed around the requirement for direct crew visual acquisition of the PL until completion of the OMS burn, and the track of the PL through the overhead window is shown in figure 5-28.

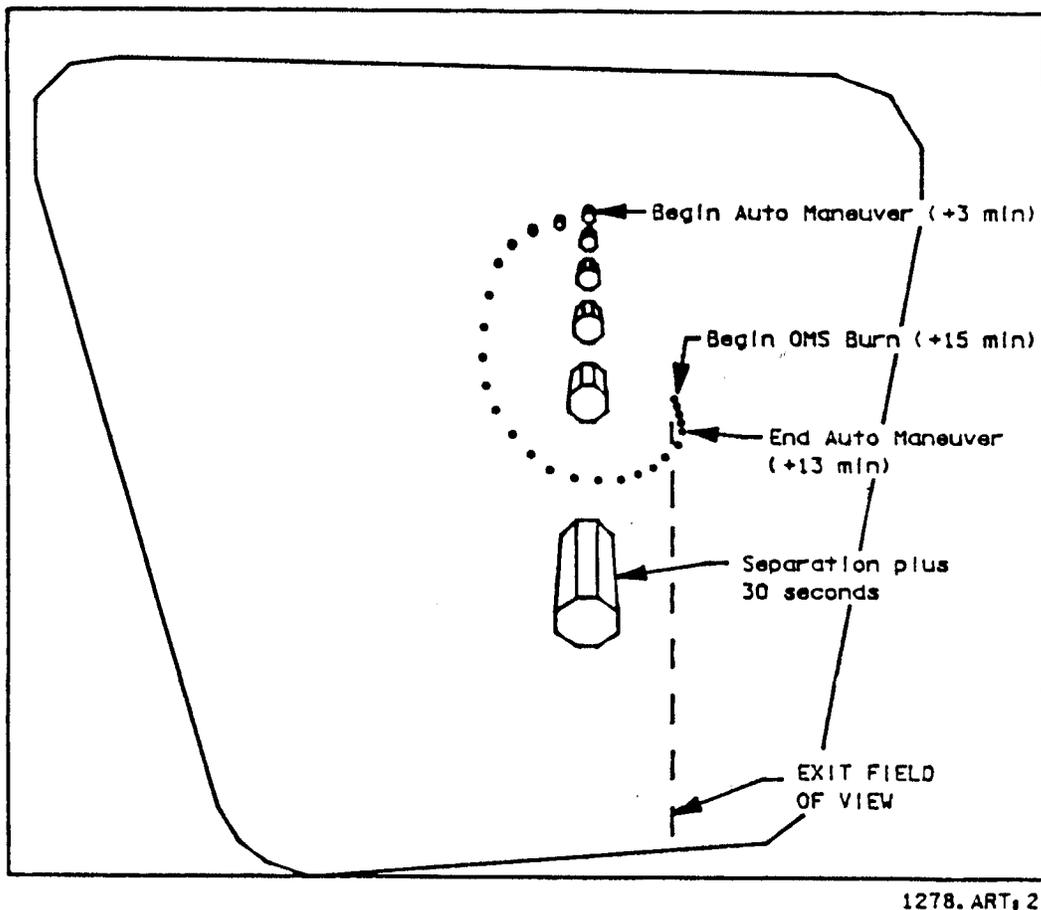


Figure 5-28.- View of PAM-D SEP from aft station through overhead window (PL shown every 30 sec).

The final issue is the Orbiter protection attitude to be maintained during the PAM-D SRM firing. Tile damage is minimized by placing the PL LOS at an angle to the Orbiter belly, as shown in figure 5-29. This attitude is maintained inertially for about 6 minutes after SRM ignition to allow the Orbiter to pass through the flow field. Current planning places the Orbiter at an angle of 50° to the PL LOS. The orientation is maintained through use of REL NAV functions.

Separation sequences are described in detail in the "Payload Assist Module Delta Class (PAM-D) Flight Procedures Handbook," JSC-20315, Final, May 15, 1985.

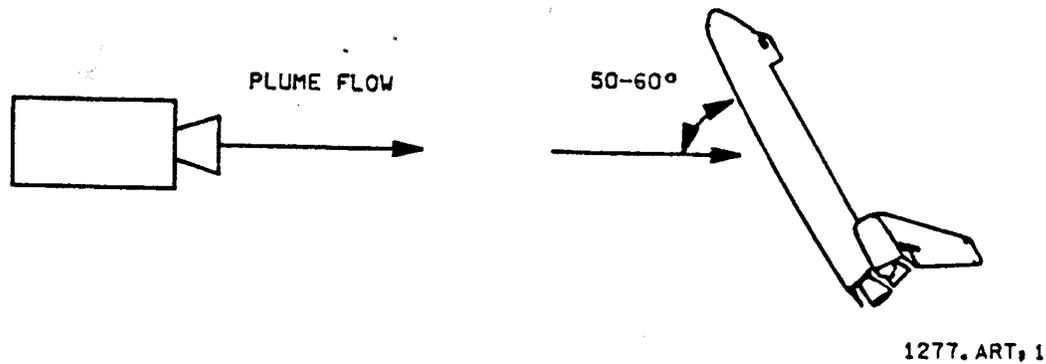


Figure 5-29.- Orbiter window protection attitude at SRM ignition.

5.4.1.2 Spring Ejection (IUS)

The IUS class of spring ejected payloads presents a different kind of problem from the PAM. Standardization is equally important, and two generic deploy sequences have been designed; they are called "ascending node solid rocket motor (SRM)" and "descending node SRM". The IUS has an active attitude control system (ACS), which allows greater flexibility for Orbiter attitude at ejection. The IUS/PL is spring ejected at 0.4 ft/s, at an angle of 58° above the Orbiter +X axis, with the Orbiter holding a solar track attitude via a selectable body vector that places the Sun on the belly of the Orbiter. This allows the IUS/PL to depart along the Orbiter shadow (until soon after the -X burn). Thus, the IUS/PL deploy vector has a marked out-of-plane component. The small Orbiter separation burn also has a large out-of-plane component. In fact, the Orbiter attitude at deploy is such that the relative motion between the IUS/PL and the Orbiter after the backoff maneuver is purely out of plane (the IUS/PL departs horizontally to one side of the V-BAR, while the Orbiter departs horizontally to the other side). These characteristics require that the Orbiter will have to be more active during IUS separation than during PAM separation.

Both ascending node and descending node SRM sequences have similar separation profiles. Deploy occurs with DAP in free drift and low Z mode. There is a 1-minute coast following ejection, followed by a 2.2 ft/s -X RCS burn (8 seconds on THC), still in free drift. Cross-coupling provides a negative pitch rate (0.8 deg/s), and the crew nulls this rate when the Orbiter has pitched down 70° by selecting inertial attitude hold (DAP ROT: DISC/DISC/DISC). This places the IUS line of sight out the overhead windows. The solar tracking option on UP is canceled (ITEM 21 EXEC). To minimize RCS contamination on the PL, the Orbiter stays in low Z mode and delays maneuver to the OMS burn attitude until deploy + 8:00 minutes. This attitude is computed so that a line of sight exists between the IUS and the Orbiter payload interrogator (PI) antenna for postdeploy commanding (including SV transfers) and telemetry.

The OMS burn is computed considering both Orbiter/PL separation at SRM ignition and also subsequent orbit management (e.g., deorbit burn requirements and cross-range for landing). This specialized planning is done because the size of the OMS burn for the IUS is greater than for a PAM deploy (a larger separation is needed since the IUS SRM is larger than the PAM SRM). In general the burn for ascending injections will be about 38 ft/s pitched down 20° from local horizontal, and for descending injections it will be about 30 ft/s pitched down 5°. No low Z is selected just prior to entering the OMS 2/ORBIT OMS BURN cue card.

Following the OMS burn the Orbiter maneuvers to a payload viewing attitude which tracks the IUS with the Orbiter -Z axis (the maneuver is performed in NORM jets). Loss of IUS/PI lock occurs about +32:00. At deploy + 39:00 the Orbiter maneuvers (in NORM) to window-protect attitude, which is identical to that of the PAM attitude described above, and maintains attitude for at least 6 to 10 minutes after SRM TIG. The minimum safe range for SRM ignition is 10 n. mi.; after nominal separation and 55 minutes, range is 25.1 n. mi., and after 67 minutes range is 51.6 n. mi.

Note that rendezvous navigation (SPEC 33) is utilized for Orbiter pointing after the separation maneuver. RNDZ NAV is enabled about 30 minutes prior to deploy, after MCC (FDO) has uplinked a target state vector. About 5 minutes before deploy, the crew must perform an ORB to TGT SV transfer (SPEC 33, ITEM 10 EXEC) to refresh the target SV. The IUS spring separation ΔV is not represented in this SV but is small enough to ignore due to its being lost in the noise of the large OMS separation burn. This attitude pointing is required to maintain PI lock for data exchange between IUS and Orbiter. Target track also simplifies maneuvering to window protect attitude, by simply selecting body vector = 5 (Orbiter defined pitch/yaw) and loading P = 310, Y = 0, OM = 0.

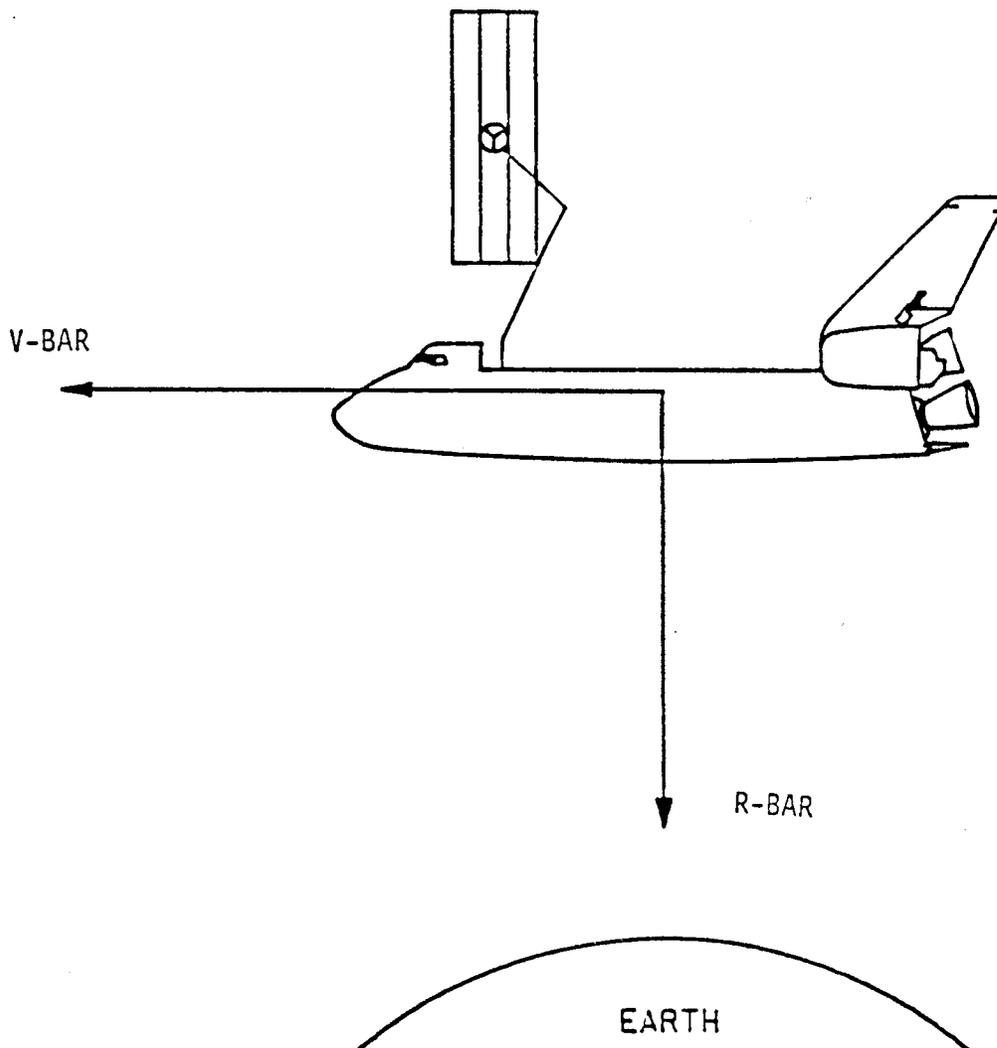
IUS SRM ignition occurs over the Equator for equatorial geosynchronous missions (interplanetary missions will not be so constrained). For the ascending node option, SRM ignition is 67 minutes after deploy, and for descending node it is 55 minutes after deploy. These times are set in order to maintain Orbiter perigee in the northern hemisphere following the OMS burn scheduled at deploy + 19 minutes. However, if there are to be significant postdeploy maneuvers which affect perigee, this consideration loses weight. For many new payloads, these considerations are also not significant and the TIG may follow deploy by anywhere between 55 and 67 minutes. A future standardized TIG of +60 minutes is under consideration.

IUS guidance can actually accommodate an off-nominal deploy at any point in the orbit. In this contingency, the IUS knows to delay ignition until the next opportunity.

For IUS deploy procedures detailed rationale, see "IUS Flight Procedures Handbook", Basic, Rev B, March 1985, JSC-18392, sections 3.4.3 ("Deploy IUS/TDRS") and 3.4.5 ("Postdeploy Separation Maneuver"), and "Inertial Upper Stage Deploy Procedures for Flight Dynamics Officers", IUS PROC 2142, Rev B, January 24, 1986. The foregoing discussion only summarizes the procedures and rationales.

5.4.1.3 RMS Deploy - Generic

PL's deployed by the RMS will typically be unique, with specific requirements that must be handled on a case-by-case basis. However, for many PL's it is anticipated that an R-BAR separation will be optimal because of low plume impingement on the PL because of utilization of orbital mechanics effects. In this scheme, the Orbiter begins in a ZLV attitude, above or below the PL depending upon relative drag and/or mission continuation requirements. Assuming for the moment that these constraints place the Orbiter below the PL, we have the relative geometry shown in figure 5-30. This selection criterion is usually required payload attitude.



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Figure 5-30.- Typical RMS deploy geometry (Orbiter below PL).

At the time of PL release, a small opening rate will begin to develop, strictly due to the differential orbit altitude. However, this opening rate is so small that it is not practical, in the general case, to depend solely on it. So while the PL is in the "quiet zone," a small opening rate is added using low Z, of <math><0.5\text{ ft/s}</math>. This will tend to force the Orbiter down, and because of orbital mechanics, in front of the PL (fig. 5-31).

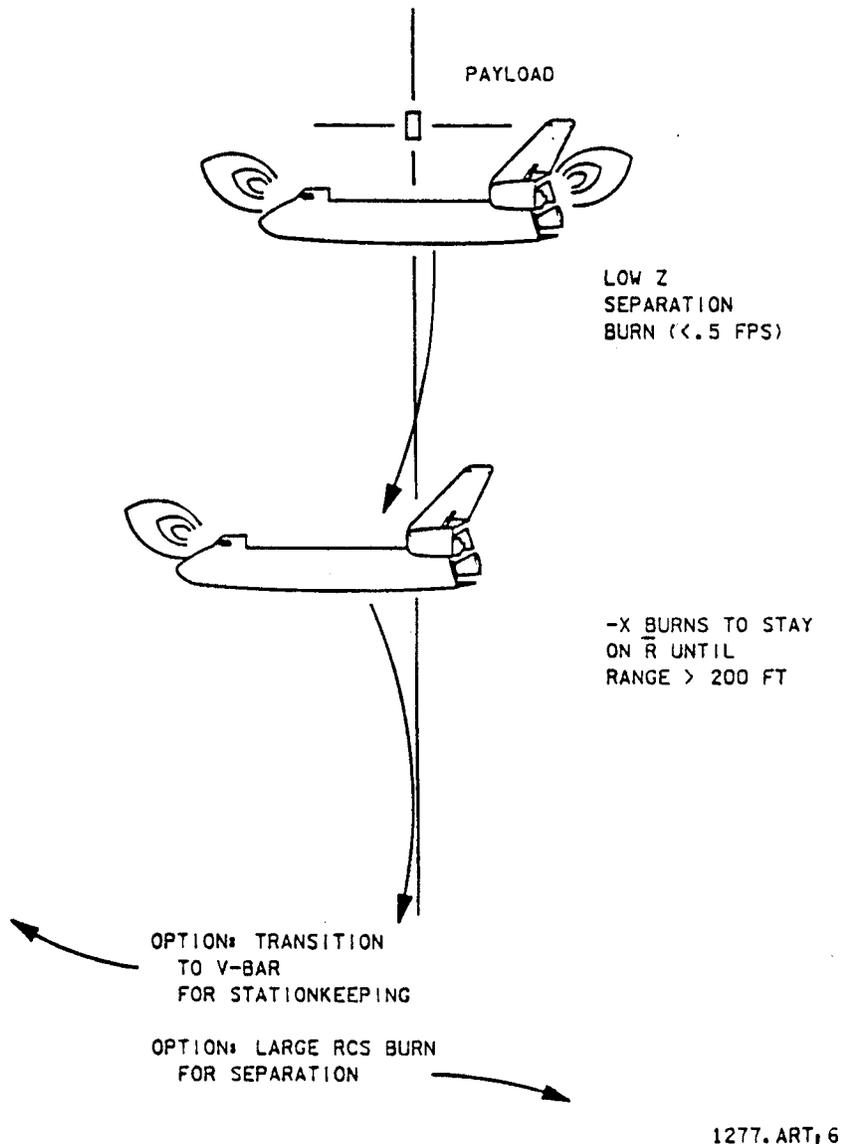


Figure 5-31.- Orbiter separation following RMS deploy (PL-centered LVLH frame of reference).

However, since it is a radial burn, with no other forces acting on the system, recontact would occur in one REV. So until a separation of about 200 feet, retrograde MNVR's are performed as required to keep the Orbiter on the R-BAR. This has the effect of lowering the Orbiter orbit and increasing the opening rate. Then as the Orbiter drifts below and in front of the PL, an option is available. If required, the Orbiter may transition up to the V-BAR and stationkeep during PL checkout. Or a larger separation MNVR with the RCS may be performed, providing a large opening rate and removing the requirement for crew monitoring of the PL.

It can be seen that in this sequence no thrusters are ever fired directly at the PL, reducing plume overpressure and contamination to a minimum.

For a PL which is not plume sensitive at all, it is likely that starting with the Orbiter on the PL V-BAR will be very fuel efficient. In this case, no radial burns are required, and maximum separation can be achieved in an efficient Hohmann fashion.

Many other separation profiles have been proposed, both for the general case and for specific PL's. Due to lack of definition and/or general application, these will be discussed as needed in supplemental documentation.

5.4.1.4 RMS Deploy (SPARTAN-class)

Separation profiles for SPARTAN-type payloads must be individually crafted due to highly variable mission-specific factors. These include payload pointing requirements, grapple fixture locations, and crew constraints on the variety of nominal versus contingency deploy profiles and RMS procedures.

Although the first SPARTAN mission was 51-G, that profile should not be considered a model for later profiles. The 51-L profile would be a much better guide to design such a profile, and the following discussion is based on that mission.

Configuration of aft station for deploy is essentially identical to configuration for rendezvous (fig. 4-4) except that on the SM ANTENNA SPEC following self-test, the "RDR RNG MIN" is selected (ITEM 2), and the -Z COAS and various cue cards are not installed. DPS configuration is also identical (section 6.1.1).

RMS operations to power up, to grapple, and to unlatch, unberth, and maneuver the payload are standardized; see the 51-L SPARTAN book.

Rendezvous navigation is enabled similar to that for rendezvous (section 4.1.6), but with several distinct differences. First, RR is the selected sensor (ITEM 13). Second, an ORB to TGT SV transfer is performed (ITEM 10 EXEC) since the starting point is known.

The Orbiter is maneuvered to release attitude about 45 minutes predeploy. For 51-L the attitude was approximately belly forward, left wing down, nose left of orbit motion.

After release, the Orbiter stationkeeps for about 10 minutes to observe the SPARTAN maneuvers which signify proper payload functioning. If there are no maneuvers, the SPARTAN is retrieved and berthed.

The separation burn is performed "no low Z," 2.0 ft/s +Z, 5 seconds on the THC (out). Low Z is then selected. This is a posigrade burn along the V-BAR.

Following separation, radar acquisition is performed after about 3 minutes. If there is no lock-on within 2 more minutes, the crew performs the "AUTO TRACK ACQ" cue card (section 4.3.2). If the RR fails, the crew waits until the scheduled STRK ACQ block, and performs S TRK NAV.

RR navigation during separation is similar to that performed for the first radar acquisition in rendezvous, section 4.1.31 and figure 4-8, with the following modifications. COVAR REINIT (ITEM 16 EXEC) is immediately performed, since this is the first navigation processing. Since SV SEL initially is PROP, the optional block is performed and SV SEL becomes FLTR. Following that, on the SM ANTENNA display the RDR RNG AUTO is selected (ITEM 1), replacing the previously selected RDR RNG MIN. Since there was no previous S TRK, the "RATIO > 1.0" test fails through to the second test, with "Force 3 marks" being the only corrective action taken. Once NAV data is being accepted, the Orbiter goes to -Z axis target track with OM = +180.

The separation profile looks very much like figure 5-48, with the Orbiter moving forward and higher, then curving back and passing about 2000 feet above the payload at about 19 minutes after separation.

Approximately one REV after deploy, STRK acquisition is performed. In general this procedure is similar to the rendezvous S TRK TARGET ACQ procedure discussed in section 3.3.2.1 (fig. 3-13), with several significant differences as follows. Once a star present is detected, angles (currently in "accept" for RR data) must be inhibited (ITEM 12 EXEC), and the STRK must be selected (ITEM 12 EXEC). Currently, the FLTR SV is selected. Once STRK marks are accepted, the FLTR SV (which has been validated through the accomplishment of a successful STRK lock-on) is saved away in PROP (the same thing is done, for the same reasons, after the second STRK acquisition during nominal rendezvous operations -- see section 4.1.22). If there is no STRK acquisition after 5 minutes, the crew goes to contingency procedure for "S TRK TARGET ACQ - RR FAIL."

After about 2 hours the separation sequence terminates. Rendezvous navigation is disabled much as in section 4.1.74, with some additions: the UP tracking is canceled (ITEM 21 on UP), and IMU DES on GNC 21 IMU ALIGN is performed via ITEM 7 (8,9), (no*); i.e., the deselected IMU is reselected. Finally, Ku-band is configured for COMM (same as section 4.1.69). The specialized rendezvous book is exited until the retrieval rendezvous begins approximately 36 hours later.

5.4.1.5 RMS Deploy (HST Class)

Some payloads are large and heavy and have very stringent contamination constraints during deployment. Examples are the LDEF and the HST (also the SMM and ERBS). The following separation profile is a generic description based on HST preliminary procedures.

There are two burns planned for HST separation, labeled SEP 1 and SEP 2. Deploy pads are prepared for both: SEP 1 is preplanned and the only real-time specified data is TIG; SEP 2 is a second RCS burn which requires TIG plus updated data on TV roll, vehicle weight, plus PEG 7 ΔV 's. An IMU DES (deselect) is also specified in anticipation of an STRK pass.

Deploy attitude for HST will be biased +X solar inertial, and deployment occurs near orbit noon. The result will be an approximately belly-forward tail-down Orbiter attitude (-XLV, YPOP), but with the +Z axis somewhat to the left or right of the V-BAR depending on beta angle.

Release accuracy for LDEF and SMM was required to be within 0.01 deg/s of desired rates. For all large payloads (HST included), free drift is maintained for 60 to 120 seconds prior to release, in an effort to minimize attitude rates on the payload following release.

SEP 1 is a 0.5 ft/s low Z mode posigrade burn for LDEF, SMM, and HST. SEP 2 is performed approximately one quarter REV later, when the Orbiter is about 600 feet above the HST on the R-BAR, and is 1 ft/s posigrade NORM Z mode from the -X RCS. A standard RMS powerdown procedure follows the SEP 2 burn.

Alternate candidate separation profiles include a sunrise deploy down the +R-BAR (see the SPAS profile, STS-7), with low Z mode 0.25 ft/s RCS followed by -X firings to maintain position on R-BAR until a range of several hundred feet. At a range of 500 feet a +X burn may be performed to accomplish final separation (other variations are also under consideration). These options are driven almost entirely by payload requirements.

For HST/LDEF/SMM, RR acquisition and navigation are performed similar to Spartan-class deploys. Target track is established with the Orbiter -Z axis. Approximately one REV after deploy, for HST an STRK pass is performed as on the SPARTAN-class deploy missions. At 2 hours into the deploy, rendezvous NAV is terminated and the Ku-band is reconfigured for COMM mode.

5.4.2 Generic Sep Procedure

An all-purpose separation procedure (the "1-2-3 maneuver") has been developed and validated for generic use. Possible applications include PL deploy, postrepair/inspection departure, and some types of PROX OPS breakout. It is especially applicable if the Orbiter is in an inertial hold and has left the TGT V-BAR, or if the Orbiter/TGT relative position is not well known.

The procedure is found in the FDF ORB OPS C/L. Procedural rationale is described in the following sections.

5.4.2.1 Set Up Aft Station

This step is shown in figure 5-32.

A6U	✓SENSE - as reqd
	DAP: A/MAN/NORM
	DAP TRANS: as reqd
	DAP ROT: DISC/DISC/DISC
	FLT CNTLR PWR - ON

Figure 5-32.- Set up aft station checklist.

DAP TRANS options are pilot's choice depending on the size of closing rate. Over 1 ft/s should be done in DAP TRANS:NORM, with transition to DAP TRANS:PULSE for the last half foot/second of translation.

5.4.2.2 Obtain Visual Contact Through OVHD Window

This step is shown in figure 5-33.

<p>DAP ROT: as reqd RHC - as reqd</p> <p>When adequate visual contact obtained, DAP ROT: DISC/DISC/DISC</p>

Figure 5-33.- Visual contact through OVHD window checklist.

This establishes TGT LOS near the Orbiter -Z axis in preparation for translation maneuvers. The DAP ROT options are chosen based on how far and fast the -Z axis must be rotated.

5.4.2.3 Null Closing Rate

This step is shown in figure 5-34.

<p>THC - +Z (dn - -X SENSE) (out - -Z SENSE) as req'd to null closing rate</p>
--

Figure 5-34.- Null closing rate checklist.

Range rate may be known from initial conditions, from known maneuver history, or (most likely) by direct visual observation when very close (inside RR track range) to TGT.

5.4.2.4 Perform RR ACQ (If Desired)

This step is shown in figure 5-35.

A1U	KU MODE - RDR PASSIVE RADAR OUTPUT - HI KU - AUTO TRACK KU CNTL - PNL Slew antenna to target ✓KU TRACK tb - gray If no TRK, KU SEARCH - SEARCH (tb-gray) If no lock-on within one minute, repeat SEARCH as convenient
-----	--

Figure 5-35.- Perform RR ACQ checklist.

This may only occur after separating beyond radar track minimum range. Note that radar is in AUTO track since there is no PL SV to automatically provide navigated pointing angles.

5.4.2.5 Obtain ~1 FPS Opening Rate

This step is shown in figure 5-36.

A6U	DAP TRANS: NORM/NORM/NORM THC - +Z for 3 sec * If Low Z (MCC call) * * THC - +Z for 12 sec *
-----	---

Figure 5-36.- Obtain ~1 FPS opening rate.

The THC sense is the same as in section 5.4.2.3 for nulling the closing rate. The 3-second burn imparts the desired opening rate. Actual ΔV may be monitored on the AVG G display on SPEC 33, but such precision is not required for a successful safe separation. This is the "1" part of the "1/2/3" MNVR.

5.4.2.6 Perform Out-Of-Plane MNVR

This step is shown in figure 5-37.

	GNC UNIV PTG
CRT	CNCL - ITEM 21 EXEC GNC, OPS 202 PRO
	GNC ORBIT MNVR EXEC
	RCS SEL - ITEM 4 EXEC (*)
	Set TIG to current time +2:00
	TGT PEG 7 ΔV_x - ITEM 19 +0 EXEC
	ΔV_y - ITEM 20 +2 EXEC
	ΔV_z - ITEM 21 +0 EXEC
	LOAD - ITEM 22 EXEC
	TIMER - ITEM 23 EXEC
	$\sqrt{VGO Z} \geq 0$; if VGO Z < 0, then
	* TGT PEG7 ΔV_y - ITEM 20 -2 EXEC *
	* LOAD - ITEM 22 EXEC *
	* TIMER - ITEM 23 EXEC *
	* $\sqrt{VGO Z} \geq 0$ *
	DO <u>NOT</u> MNVR TO BURN ATT
A6U	At TIG deflect THC to null VGOs

Figure 5-37.- Perform out-of-plane MNVR checklist.

If the burn VGO, displayed in body coordinates, shows a -Z component, this means that the intended out-of-plane maneuver will take the Orbiter directly back through the TGT plane. In this case, reload MNVR EXEC with a -2 ft/s Y burn.

The test of VGO Z simply ensures that the out-of-plane burn is away from the TGT. This is the "2" part of the "1/2/3" maneuver.

5.4.2.7 Perform Final SEP

This step is shown in figure 5-38.

```

|GNC ORBIT MNVR EXEC|
-----
CRT      ✓RCS SEL - ITEM 4 (*)

        If ΔVY (Block 6) is +2
        | TV ROLL - ITEM 5 +2 7 0 EXEC
        If ΔVY (Block 6) is -2
        TV ROLL - ITEM 5 +0 9 0 EXEC

        Set TIG to TIG from last step + 15:00
        TGT PEG 7 ΔVx - ITEM 19 +3 EXEC
                   ΔVy - ITEM 20 +0 EXEC
                   ΔVz - ITEM 21 +0 EXEC

        LOAD - ITEM 22 EXEC
        TIMER - ITEM 23 EXEC
        DAP: A/AUTO/NORM

        At TIG -8:00; MNVR - ITEM 27 EXEC (*)

A6U     At TIG deflect THC to null VGOs
        AFT FLT CNTLR PWR - OFF

```

Figure 5-38.- Perform final SEP checklist.

The $\Delta V Y$ check determines which direction out of plane was burned on the previous maneuver, to select the most easily reached TVR. The plan is to make this burn about one quarter of a REV later, which is at the point of maximum out-of-plane separation (about 2000 feet for a 2 ft/s burn). The burn is large enough to perform with +X RCS jets. This is the "3" part of the "1-2-3" maneuver.

5.4.2.8 Maneuver To Minimum Drag Attitude (-ZLV)

This step is shown in figure 5-39.

AGU	DAP: A/AUTO/VERN
CRT	GNC, OPS 201 PRO
	GNC UNIV PTG
	✓TGT ID - 2
	BODY VECT -3
	OM - 180
	START TRK - ITEM 19 EXEC (CUR *)

Figure 5-39.- Maneuver to minimum drag attitude (-ZLV) checklist.

Drag is of concern because of potential differential drag effects (section 2.7.1). Hence, the -Z axis is pointed to Earth center, and tail is rotated into +V-BAR.

5.4.3 Contingency

Contingency separation procedures can be divided into several broad classes: those which allow an Orbiter maneuver to a planned deploy attitude, and those which result from an inadvertent deployment or must be performed from a random relative position to the TGT.

5.4.3.1 Rendezvous Breakout Procedure

This breakout has two periods of applicability, from the sunset after T_i until MC2, and from MC3 until PROX OPS. If breakout criteria are met between MC2 and MC3, breakout must be delayed until MC3. The reason for this is that between these intervals an OOP miss cannot be guaranteed (TGT contact may be possible). See figure 5-40.

Perform out of plane $\Delta V = 3$ fps away from TGT plane (THC - 12 sec in DAP TRANS: NORM) After 15 min, perform retrograde $\Delta V = 3$ fps OPS 202 PRO <u>GNC ORBIT MNVR EXEC</u> ✓ RCS SEL - ITEM 4 (*) TV ROLL - ITEM 50 +0 EXEC Set TIG to out-of-plane burn +15:00 TGT PEG 7 ΔV_x - ITEM 19 -3 EXEC ΔV_y - ITEM 20 +0 EXEC ΔV_z - ITEM 21 +0 EXEC LOAD - ITEM 22 EXEC TIMER - ITEM 23 EXEC At TIG -8:00; MNVR - ITEM 27 EXEC (*) DAP: B/AUTO/NORM (✓ ROT DISC RATE = .5) At TIG deflect THC to null VGOs

Figure 5-40.- Rendezvous breakout procedure checklist.

During flight techniques discussions, there was a strong desire to develop a single, propellant-efficient breakout maneuver sequence independent of relative position. The result was a 3 ft/s out-of-plane maneuver away from the TGT plane, followed 15 minutes later by a 3 ft/s retrograde maneuver. This sequence provides an Orbiter c.m. to TGT c.m. miss distance of at least 500 feet. Because of trajectory dispersions, this sequence cannot be initiated everywhere between T_i and V-BAR arrival. Specific initiation times have been established depending on Orbiter propellant, Orbiter system status, and the TGT sensor data history (sec. 4.6.2).

In section 4.6.2, the note "nominally Orbiter Y body axis" was included to define which propulsion system contained the propellant for the out-of-plane maneuver (bingos). This note assumes a Y-POP, -Z TGT track Orbiter attitude driven by the use of either the RR, -Z STRK, or the COAS. If the -Y STRK is used, the Orbiter attitude would be inconsistent with the Y body thrusters providing an out-of-plane maneuver. A maneuver to burn attitude is prohibited because of the delay in initiating the sequence and the loss of TGT acquisition while still on an intercept trajectory. In this scenario, the propellant for the out-of-plane maneuver would have to come from another

propulsion system. Similarly, the note "Orbiter +X body axis" was included for the retrograde maneuver. However, this maneuver is executed in burn attitude.

Further information on this breakout maneuver sequence can be found in Orbit Flight Techniques No. 82 (Nov. 17, 1987) minutes.

5.4.3.2 PROX OPS Breakout Procedure

This procedure is shown in figure 5-41.

```

If on +V-BAR,
  Perform 2 fps posigrade burn
  (THC - +Z, 5 sec in DAP TRANS: NORM, NO LOW Z)

If on -Vbar,
  Perform 2 fps retrograde burn
  (THC - +Z, 5 sec in TRANS: NORM, NO LOW Z)

If on -Rbar or in transition +Vbar to -Rbar,
  Perform 1 fps burn away from the target
  (THC - +Z, 3 sec in TRANS: NORM, NO LOW Z)
  After 10 min, perform 1 fps posigrade burn
  (multi-axis)
  |GNC ORBIT MNVR EXEC|
  ✓RCS SEL. ITEM 4 - (*)
  TIG = Initial sep + 10 min
  PEG 7 ΔVX = +1, ΔVY = 0, ΔVZ = 0
  LOAD - ITEM 22 EXEC
  TIMER - ITEM 23 EXEC
  DAP: A/AUTO/NORM
  TIG - null VGOS

If none of the above, or if inertial stationkeeping
has been initiated, perform SEP MANEUVER (ORB OPS)

```

Figure 5-41.- PROX OPS breakout procedure.

Post-V-BAR arrival, the abort maneuver sequence will be:

- A. If stable on the +V-BAR, perform 2 ft/s posigrade MNVR (nominally Orbiter +Z body axis, NORM Z translation mode) ASAP. If stable on the -V-BAR, perform 2 ft/s retrograde MNVR (nominally Orbiter +Z body axis, NORM Z translation mode) ASAP. While on the +V-BAR where the relative position of the Orbiter and TGT is well defined, a single abort MNVR can be performed. If stationkeeping, 2 ft/s will produce approximately a 5 n. mi. per REV opening rate; if closing or opening when the MNVR is executed, the opening rate will be proportionately smaller or greater, respectively. The direction of the MNVR was chosen to ensure no immediate recontact with the TGT. The note "nominally Orbiter +Z body

axis, NORM Z translation mode" was included to define which propulsion system contained the propellant for this MNVR (bingos).

- b. If stable on the -R-BAR or initially transitioning from the +V-BAR to the -R-BAR, with the TGT in view out the Orbiter overhead window, perform 1 ft/s away from the TGT (nominally Orbiter +Z body axis, NORM Z translation mode) followed 10 minutes later by a 1 ft/s posigrade MNVR (Orbiter +X body axis). A -R-BAR approach differs from the more standard V-BAR approach by including a transition from the +V-BAR to the -R-BAR and then stationkeeping on the -R-BAR. During this time frame, a more propellant-efficient abort maneuver sequence than the "generic" separation maneuver exists. This sequence is consistent with the V-BAR approach abort maneuver sequence. The 1 ft/s MNVR away from the TGT produces an initial opening rate so the 1 ft/s posigrade MNVR can be performed with no potential for recontact. This sequence will initiate an opening rate of 2.5 to 5 n. mi. per REV depending on the relative position of the Orbiter and TGT when the sequence is executed. The notes "nominally Orbiter +Z body axis, NORM Z translation mode" and "Orbiter +X body axis" were included to define which propulsion systems contained the propellant for these MNVR's (bingos).
- c. If neither "a" nor "b" applies, perform separation maneuver in orbit OPS checklist ASAP (see section 5.4.2). If neither condition a nor b, the relative position of the Orbiter is not well-defined. Hence, the "generic" separation maneuver in the Orbit OPS checklist should be used. This procedure is independent of relative position (within PROX OPS) and will initiate an overall opening rate of 5 to 10 n. mi. per REV depending on the relative position when the sequence is initiated.

During an inertial approach, inertial stationkeeping, or flyaround, the Orbiter crosses the +V-BAR and 25 percent of the time flies above, and in front of, the TGT. If the Orbiter is at one of these relative positions, the abort maneuver sequences described in a and b could be used and 4 ft/s propellant could be saved. However, it is unwise to have more than one abort procedure during a given piloting task. Hence, only the "generic" separation procedure is used.

5.4.3.3 Jettison

Jettison is the class of contingency procedure where the actual Orbiter/PL separation is accomplished through deliberate crew action. Numerous jettison scenarios can be constructed, including the following:

- RMS - required if the RMS cannot be berthed and/or stowed, and the PLBD therefore cannot be closed.
- Ku-band antenna - required if the antenna cannot be stowed, therefore the PLBD cannot be closed.

- PL - required if a PL which was unberthed (but not intended to be deployed) cannot be reberthed, or if a PL not intended to be deployed has become unsafe for deorbit.
- PL/RMS - may be required if the RMS end effector cannot be removed from the grapple fixture (may be able to remove via EVA).

In all of these jettison situations, a simple efficient Orbiter separation can be performed. This technique places the Orbiter XLV, vertical stabilizer trailing. The jettison, which is nonimpulsive in all of these cases, is performed, followed by a 1 ft/s posigrade Orbiter translation. After about 2 minutes (roughly 130 feet of separation), another 1 ft/s posigrade Orbiter burn is accomplished to achieve a larger opening rate. The rationale for the two-burn sequence is that the first burn initiates opening with minimum tumbling due to plume, and the second burn gives greater desired SEP rate. This was specifically developed for RMS. The subsequent relative motion is shown in figure 5-46.

The RMS jettison procedure is found in the PDRS (A11) book, and the KU-BD ANT JETTISON is found in the ORB OPS book. The actual steps and rationale, plus differences between them, are described below (xxx refers to jettisoned object).

1. Prepare for jettison and perform between sunrise and noon if possible. This enhances visibility of xxx during initial separation.
2. AUTO MNVR to -XLV. See figure 5-42.

CRT	GNC UNIV PTG
	✓START TIME at least 15 min prior to sunrise
	✓TGT ID +2 (earth center)
	BODY VECT +2 (-X axis)
	OM +0
	Initiate TRK
A6U	DAP:A/AUTO/VERN
A6U	FLT CNTRLR PWR - ON
	EVENT TIMER MODE - UP
	CNTL - STOP
	TIMER - RESET
A7U	✓Lighting - as reqd

Figure 5-42.- AUTO MNVR to - XLV checklist.

7. Separate (see figure 5-45).

<u>NOTE</u>	
After JETT. initiate opening rate ASAP. Minimize other THC/RHC inputs	
Maintain xxx in B CCTV	
JETT+	
0:01	WHEN JETTISON COMPLETE. TRANSLATE AWAY THC +Z. 2 sec (1 ft/sec) (-X sense: THC dn) (-Z sense: THC out)

Figure 5-45.- Separation checklist.

This second burn (fig. 5-46) can be performed either on time (after 2 minutes, for PDRS) or on range (at 100 ft, for Ku-band). Although they should be equivalent, it is important to observe the jettisoned object and verify that both conditions are met.

SENSE - as reqd
THC +Z, 2 sec (1 ft/sec) (-X sense: THC dn) (-Z sense: THC out)
Maintain visual contact with xxx in OVHD window using RHC

Figure 5-46.- Second SEP burn.

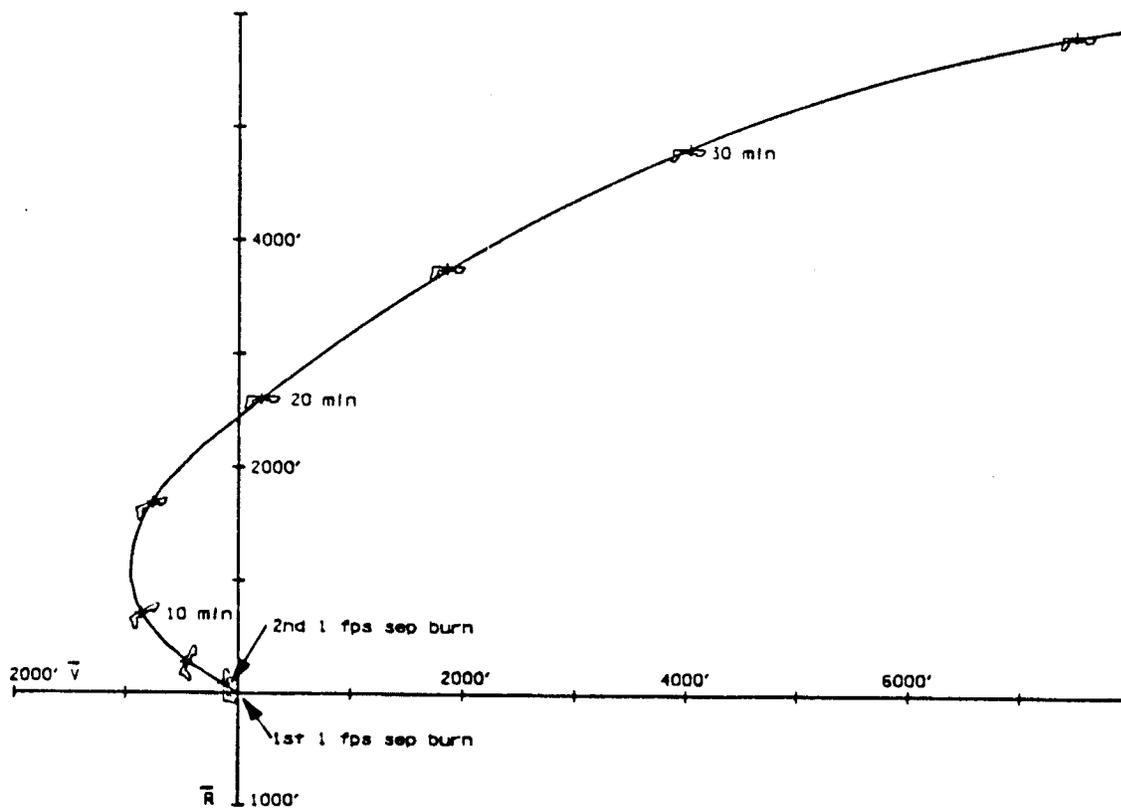
The jettisoned body is kept in visual acquisition by the crew as long as possible to verify the opening rate, and from figure 5-48 it can be seen that after about 20 minutes this places the Orbiter in -ZLV. Since all PL's and appendages which have been studied to date have higher relative drag than the Orbiter, and -ZLV is the lowest Orbiter drag profile, this will provide a further long-term opening rate as the other body tends to drop lower and therefore travel faster. In a jettison situation where deorbit will follow closely after jettison, a mirror image separation can be performed such that each burn will be retrograde. In this case the relative drag effects can be ignored.

8. Go to new attitude when xxx no longer visible (see figure 5-47).

A6U	FLT CNTRLR PWR - OFF
	<u> GNC UNIV PTG </u>
	✓TGT ID +2
	BODY VECT +3
	OM +0
	START TRK - ITEM 19 EXEC (CUR *)
A6U	DAP: A/AUTO/VERN

Figure 5-47.- New attitude checklist.

9. Perform systems cleanup.



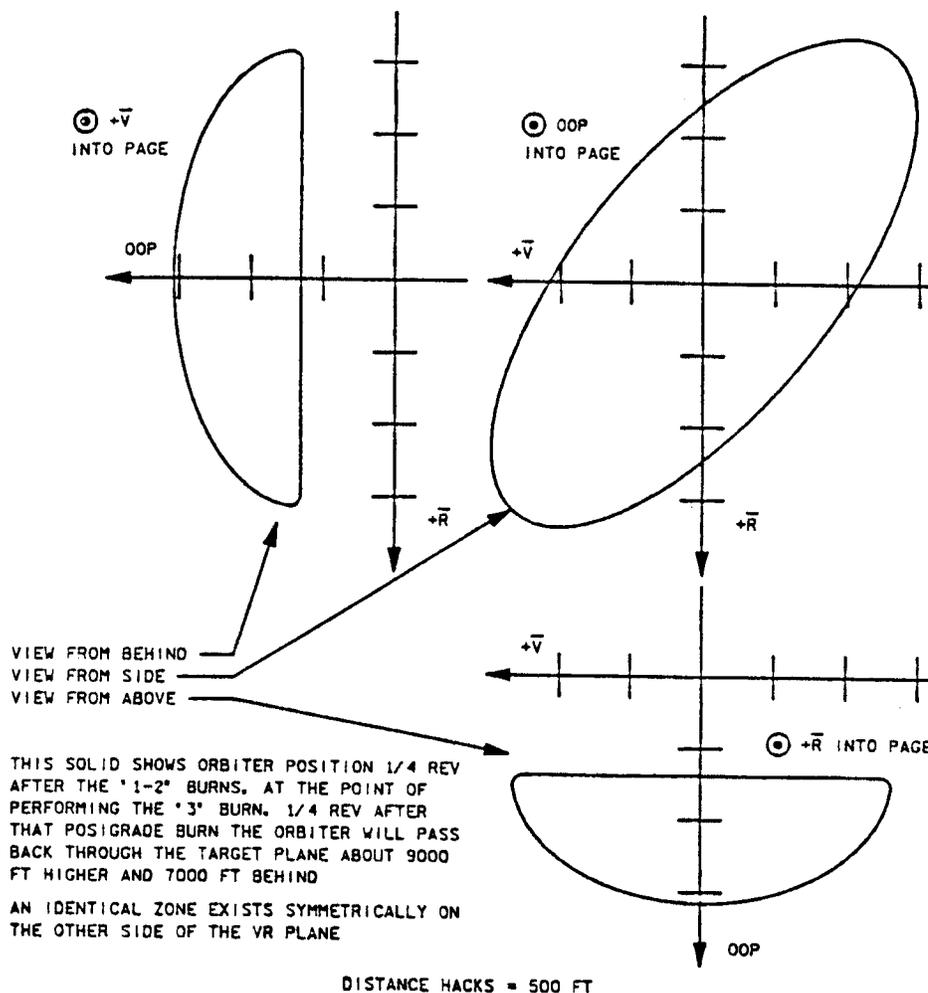
1364. ART. 1

Figure 5-48.- Orbiter separation trajectory following jettison.

5.4.3.4 Inadvertent/Immediate Release

Although inadvertent/immediate release is generally considered to be highly unlikely, it is a sufficiently serious situation to require some attention. The major difficulty with an inadvertent/immediate release is that in general it can happen with the Orbiter in any LVLH attitude, so simply backing away from the body is not the answer. If the back-off maneuver happens to be out of plane, a recontact situation may occur half a REV later. If the back-off were radial, recontact could occur one REV later. A procedure which can handle the general case is the generic "1-2-3 burn" described in 5.4.2, especially beginning in step 5. See figure 5-49.

This procedure does not necessarily provide for crew visibility of the other body throughout the SEP sequence, but is an efficient and relatively simple procedure, minimizing crew training.



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Figure 5-49.- Generic ("1-2-3") Separation

SECTION 6 MCC REAL-TIME SUPPORT

During rendezvous and proximity operations, the on-orbit MCC shift will be supplemented by a special group of flight controllers (the "Rendezvous Team"). A specialized "RNDZ Flight Dynamics Officer" is also on console, along with support personnel. The FCR operator, in the "Trench" (lowest and front-most FCR row) between FDO/TRAJ and GN&C/PROP, is called the "Rendezvous Guidance and Procedures Officer (GPO)", call sign "RENDEZVOUS" (see figure 6-1); he has overall responsibility for the proper performance of the RNDZ C/L.

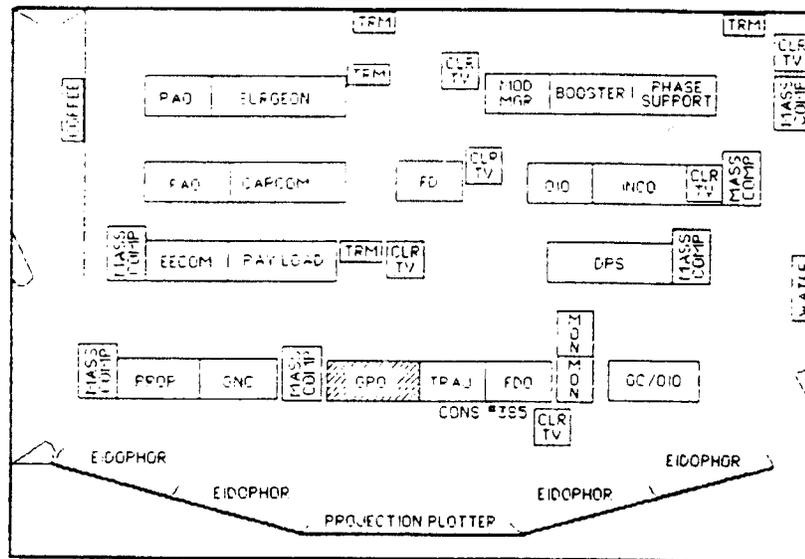


Figure 6-1.- FCR console layout.

Supporting the RNDZ GPO in the TRAJ MPSR are three consoles: Rendezvous Procedures Support ("RPS"), Orbit Navigation ("ONAV"), and Orbit Targeting ("TARGET"). A summary chart of RNDZ team members is shown in fig. 6-2. The detailed specifications of their duties, procedures and reference materials are found in the "Rendezvous GPO Team Console Handbook", JSC-22339, PRELIM, May 16, 1988, and the "Flight Dynamics Officer Console Handbook", BASIC, to appear 1988; this section provides a brief overview for operational understanding of real-time mission support.

The interrelationship and communications flows of the RNDZ Team FC's are shown in figure 6-3. The RNDZ team personnel come from the Orbit Dynamics Section (DM43), Orbit Analysis Branch (DM4), Flight Design and Dynamics Division (DM), Mission Operations Directorate of NASA-JSC, with support from the Orbit Analysis and Procedures unit (RS16), Orbit Flight Analysis Group, Flight Design and Dynamics Department, Mission Operations Division, of the Rockwell Shuttle Operations Company.

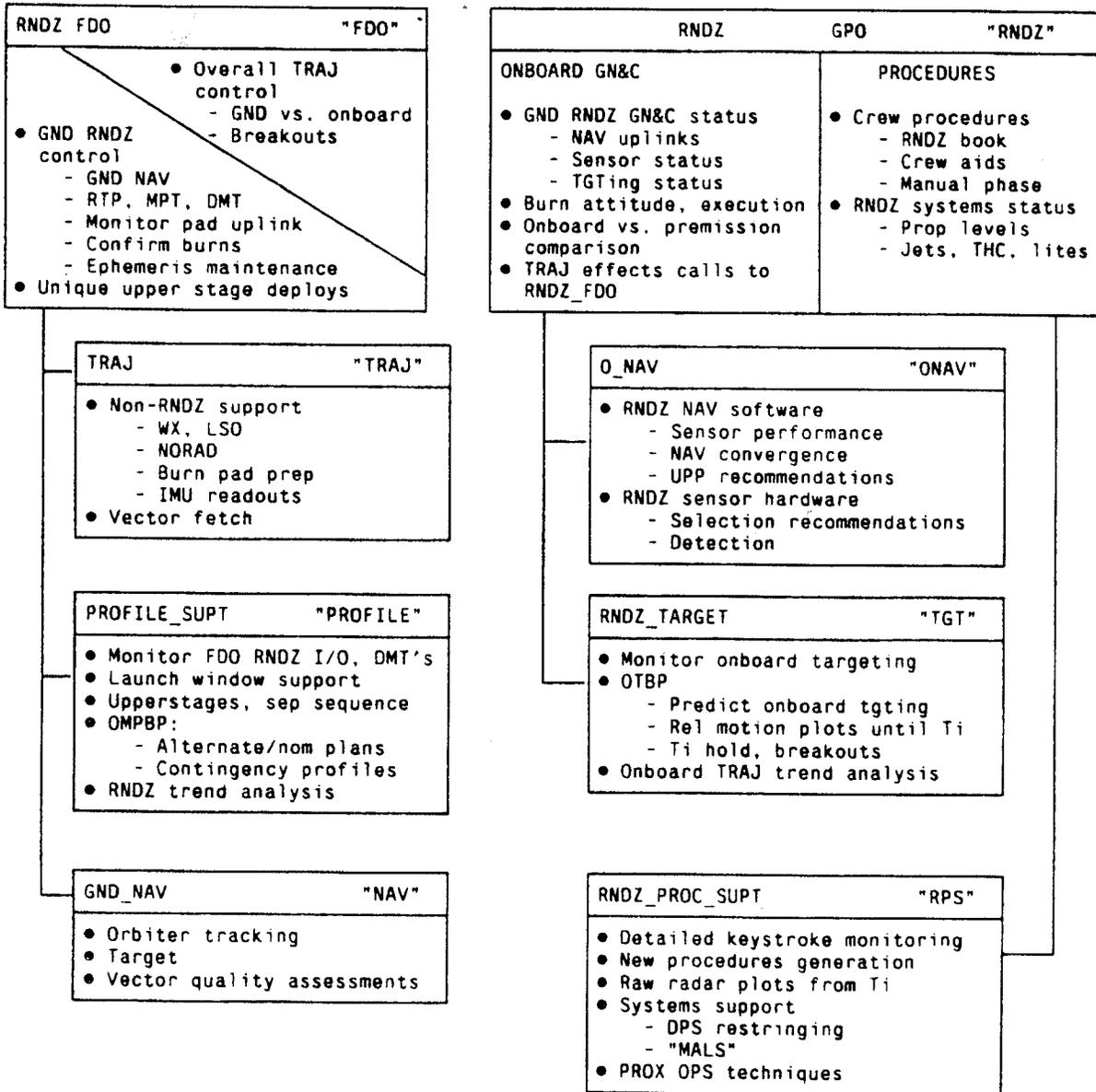


Figure 6-2.- Rendezvous real-time support.

RNDZ specialist are on round-the-clock duty during all on-orbit operations involving preparation for and execution of any rendezvous, proximity operations, or separation (with option to return) activities; a minimum team will support the planning shift prior to execute shift. This is true both for preplanned rendezvous and proximity operations and for contingency (call-up) operations. In addition, it is highly desirable that at least the GPO and minimum support personnel be on hand for all operations with the potential for close-in two-body motion in which Orbiter recontact is possible (e.g., EVA, jettisons).

The RNDZ FDO prepares and uplinks all maneuver command loads and all state vectors (Orbiter and target) as needed; he also prepares the maneuver PAD's which are voiced up. The RNDZ GPO is responsible for uplinking the covariance matrix, which acts as a filter on raw onboard navigation data being processed to improve the FLTR SV; he also prepares SEP PAD's as required.

The RNDZ GPO represents the office which has prepared the FDF RNDZ C/L (normally, the RNDZ GPO on duty during execute shift has personally been involved with the mission for 1 to 2 years and has been intimately involved in the actual procedures development and documentation work). During on-orbit operations the RNDZ team follows procedures execution and verifies proper performance, recommends contingency techniques/procedures as needed, follows the mission with attention to impacts on RNDZ procedures due to other systems anomalies, and keeps the MCC team aware of impending activities and their priorities. Navigation anomalies are analyzed and crew choice of proper SV and maneuver solutions is verified.

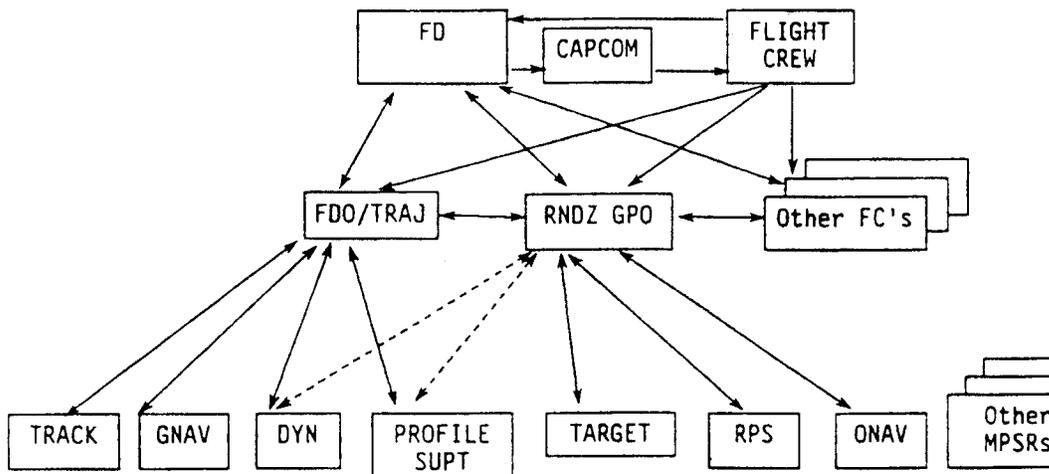


Figure 6-3.- RNDZ team.

In support of MCC monitoring, the RNDZ team uses a specialized set of displays, clocks, and indicators, in particular the MSK 1888 display called "RNDZ PROC" (fig. 6-4). They allow monitoring of: vehicle system status, attitude/errors, active DAP configuration, scratch pad lines, NAV sensor status, performance, readings, and edit status, most REL NAV, UP, and MNVR EXEC parameters, and most relevant switch positions. GMT, MET, PET, post-MC2 ET, and time-to-SR/SS are displayed. There are some parameters not displayed onboard that can be monitored in the MCC (e.g., STRK measured target brightness). Other onboard parameters are not downlisted but are monitored by the MCC during RNDZ phase by using the GNC variable parameter option (currently the SPEC 34 target set number, and the computed T1 TIG to monitor MC2 TIG slip). Still other parameters cannot be observed at all (e.g., PLB CCTV angles during prox ops ranging), and occasional crew readout would facilitate MCC appraisal of mission status. It should be stressed

SECTION 7 TETHERED OPERATIONS

The operation of separate PL's in proximity to the Orbiter has always been a RNDZ/PROX OPS operational concern. In the near future a new class of PL's will appear, those which remain physically attached to the Orbiter by tethers. Although some new flight-dynamics laws come into play, such objects are only a tether-break away from becoming classical PROX OPS subjects and many actually plan to separate rather than return to the Orbiter; furthermore, traditional monitoring and control techniques for RNDZ/PROX OPS have major applications to this new class of PL. Consequently, the flight procedures for tethered objects clearly fall within the purview of this book.

7.1 BACKGROUND

To understand tethered operations, an appreciation of the history, candidate applications, and safety concerns is required.

7.1.1 History

Tethered operations occurred in the Gemini program when the manned Gemini spacecraft was connected to the Agena booster by a 100-foot tether. Gravity gradient and artificial gravity experiments were conducted.

Current projects involve plans for both short (300 feet) tethers (on Hitchhiker G2) and long (10 to 20 n. mi.) tethers (for the Italian "TSS" or "Tethered Satellite System"). An official NASA project envisages systems that can achieve 50 n. mi. (100 km) deployment distances with new tether materials, control laws, and supporting subsystems.

7.1.2 Applications of Space Tethers

Numerous applications have been imagined for tethered objects in space. These include:

Electrodynamic -- A conducting tether moving through Earth magnetosphere generates electrical current (a 5 to 10 n. mi. tether would generate line voltage of 2 to 4 kV), or, inversely, current in a conducting tether generates thrust for orbital adjustment.

Trolling (instruments or test models) -- Instruments are lowered into normally inaccessible (in terms of longterm in situ measurements) regions of the upper atmosphere. Test models of future aerospace planes are lowered into the upper atmosphere for aerodynamic studies. Keels may be lowered into the upper atmosphere for plane changes.

Variable G -- In stable gravity gradient mode, modules moved along tethers can experience a variety of G-forces, which can be tailored to the desired applications. In dynamic, rotating systems, large accelerations can be generated for control, physical processing, or long-term human health applications.

Momentum Transfer -- Objects at the end of tethers can be released, taking momentum from a main object and imparting it to a secondary smaller object for either orbit boost or deboost. The momentum of the larger object can then be made up using high-efficiency low-thrust propulsion systems.

Constellations -- Structures can be established in stable REL positions tens or even hundreds of miles apart. For operational reasons, specialized modules (such as a docking wharf) can be separated from a main object for operations, and then retrieved, repeatedly.

7.1.3 Safety Considerations

While the theoretical applications appear to be unlimited, the key issue is whether such plans are operationally feasible. That is, can safe procedures (both AUTO and manual) be developed under which such applications can occur?

Key safety issues include (but are not limited to)

- a. System dynamics stability
- b. Tether failure
 - (1) Structural (tether)
 - (2) Attach points
 - (3) Induced (e.g., collision with debris)
- c. Reeling mechanism failure
 - (1) Jamming
 - (2) Power loss
 - (3) Overtorque reel-in
 - (4) Runaway
- d. Deployed-object anomalies
 - (1) In-line thruster fail-off
 - (2) NLOS thruster fail-on
 - (3) Dynamics

- e. Orbiter damage
 - (1) Physical impact (tiles, windows, SSME/OMS/RCS engines)
 - (2) Tether mechanism stow (versus jettison)
 - (3) Mechanical jam (e.g., Ku-band antenna, PLB doors)
- f. Contingency procedures
 - (1) Brake application
 - (2) Motor unpower
 - (3) Tether guillotine
 - (4) Boom jettison
 - (5) Separation maneuvers

Any candidate body of procedures must take into account these and other as yet undefined concerns.

7.1.4 Reference Material

A number of general reference articles are available (from which much of the material in this section has already been directly excerpted), including:

Guidebook for Analysis of Tether Applications, Joseph A. Carroll, contract RH4-394049 with Martin-Marietta (as part of NASA-MSFC contract NAS8-35499, "Study of Selected Tether Applications in Space"), March 1985.

"Controlled Tether Extends Satellite's Orbital Range," Victor Wigotsky, Aerospace America, June 1984, pp. 34-36.

"Tether Propulsion," Ivan Bekey and Paul Penzo, Aerospace America, July 1986, pp. 40-43.

"Tether Applications in Space Transportation", Joseph A. Carroll, Acta Astronautica, 1986, Vol. 13 no. 4, pp. 165-174.

Proceedings of NASA/AIAA/PSN "International Conference on Tethers in Space," September 17-19, 1986.

"Tethers in Space: The Future Nears," William J. Broad, N. Y. Times, January 7, 1986.

"Trolling the Atmosphere," Richard DeMeis, Aerospace America, June 1986, pp. 16-17.

7.2 THEORETICAL CONDITIONS

The statics and dynamics of tethered space systems involve mathematically accurate but intuitively unfamiliar features. A brief summary of the theoretical basis for such features may help in appreciating their operational implications.

7.2.1 Tension

In a weightless condition, tethered objects are unlike objects hung on cables under one g conditions, where the full weight of the object is supported by the cable. In orbit, both tethered objects are nearly in stable ballistic trajectories, and only the difference between such free trajectories and actual tethered trajectories shows up as tether tension.

Consider the example of two equal mass objects tethered 10 miles apart. Their c.m. is in a stable orbit with a known period. For a free-flying object passing 5 miles below this system c.m., relative motion would be approximately 50 miles per REV, or 50 ft/s (in accordance with the "10:1" rule of thumb for ΔH to lateral separation ratios). The lower mass, then, is moving 50 ft/s too slow for a circular orbit at its altitude, but it is still moving at nearly 25,000 ft/s anyway, so the deficit in orbit motion is a very small fraction (several tenths of one percent, in this case), and the weight "hanging" on the tether is a similarly very small fraction of the total one g weight of the lower mass (a half-ton satellite would induce only a few pounds of tether tension). A rule of thumb is that a free-hanging tethered system will experience tension equivalent to 1 percent of the one g weight of the object per 12 n. mi. of length.

Note: If the lower mass, 5 miles below the c.m., were detached, it would act exactly as if a satellite there in circular orbit suddenly performed a -55 ft/s ΔV . Then it would thus fall into an orbit with opposite end about 33 n. mi. lower while the upper mass would rise 33 miles (via the old familiar "2:1 Rule" of ΔV to ΔH ratios). This is approximately the same result discussed under "momentum exchange" applications.

Gravity gradient tension is caused by a combination of gravitational and centrifugal forces (fig. 7-1). One-third of the total force is centrifugal, due to the ROT of the LVLH system in inertial space; two-thirds is gravitational, due to the inverse square diminution of Earth gravitational attraction as distance from Earth increases.

In low Earth orbit, the magnitude of these effects depends on the size of the system. A rule of thumb specifies about 0.12 $\mu\text{g}/\text{ft}$, or 1 μg per 8 feet.

Over about a foot, the gravity-gradient forces amount to a tenth of a microgee (essentially undetectable); over the length of the Orbiter (150 feet), the gravity gradient forces amount to about 10 microgees (possibly noticeable); over a tether length of 5 n. mi., gravity gradient forces amount to several thousand microgees. Objects which are located that far from the system c.m. will experience gravity gradient acceleration fields of that size.

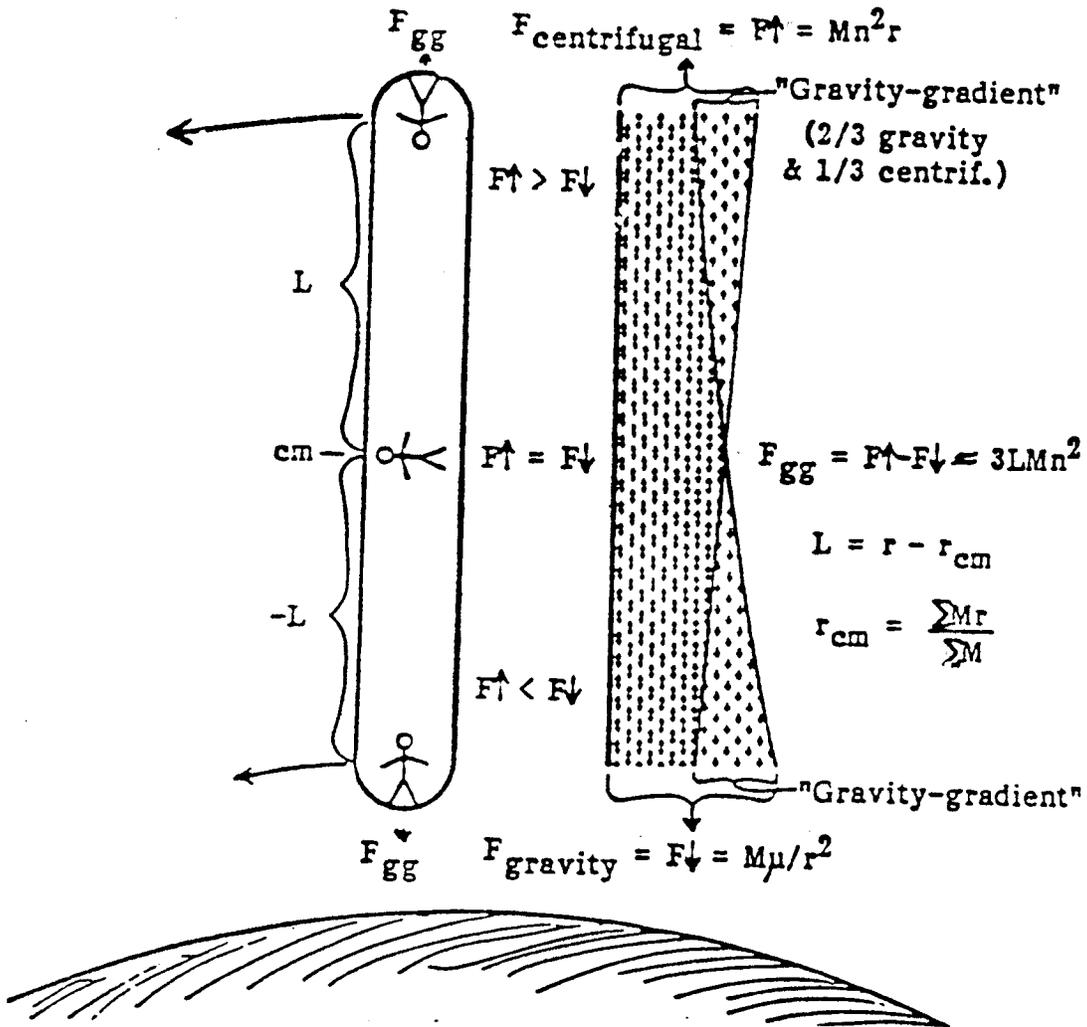


Figure 7-1.- Origin of "gravity-gradient" forces.

Practical considerations help define an Orbiter-satellite range beyond which gravity gradient forces can be relied on to safely maintain tether tension. Inside that range, other techniques (such as in-line thrusters) would be required to maintain tension. For initial TSS-S studies, that range appears to be approximately 4000 feet. For other tethered payloads, analysis may produce a different range.

7.2.2 Motion

The motion of tethered systems has been analytically studied in depth.

Changing the tether length between two end masses induces a system tilt, due to Coriolis forces. This induced tilt sets up a periodic motion called libration. As will be described below, the reverse process is also possible: in-plane libration can be damped by a judicious variation in tether reel in and reel out rates.

Libration is defined as the cyclic swinging motion of a tethered system relative to the local vertical, or the system R-BAR. The following treatment and terminology is adapted from Carroll (1985).

In-plane libration is measured with an angle θ of the tether relative to the system R-BAR. Out-of-plane libration is measured with the angle ϕ , again measured as the tether orientation relative to local vertical. For convenience, these are referred to as θ -libration and ϕ -libration.

In the extreme case, libration becomes spin, as the system begins a centrifugal ROT rather than a periodic back-and-forth swing. Such dynamics have applications both to momentum transfer techniques and potentially to non-thruster retrieval techniques.

Four aspects of libration behavior deserve notice:

First, the restoring forces grow with the tether length, so libration frequencies (at low amplitudes) are independent of tether length. Thus, tether systems tend to librate "solidly," like a dumbbell, rather than with the tether trying to swing faster than the end masses (as can be seen in the chain on a child's swing). For low orbits around Earth, libration periods are roughly an hour (θ -libration period is 0.577 times orbital period; ϕ -libration period is 0.5 times orbital period), and increase if amplitude is very large.

Second, tethered masses would be in free-fall except for the tether, so the sensed acceleration is always along the tether.

Third, the axial force can become negative for extreme swings ($\phi > 60^\circ$, or near ends of retrograde in-plane swings where $\theta > 66^\circ$), and this may cause problems unless the tether is released, or retrieved at an adequate rate to prevent slackness (or if the objects have active in-line thrusters).

Fourth, although theta-libration is not close to resonance with any significant driving forces, phi-libration is in resonance with several, such as out-of-plane components of aerodynamic forces (in nonequatorial orbits that see different air density in northward and southward passes), or electrodynamic forces (if tether currents varying at the orbital frequency are used). There are limits to the effect of such weak but persistent forces, but these limits are, in most cases, quite high. Further, when a system is in an eccentric orbit, variations in orbital rate cause librations which in turn exert periodic torques on an initially uniformly-rotating object, and in highly eccentric orbits this can soon induce tumbling.

Besides libration, other dynamic features of tethered systems are tether oscillations ("longitudinal" or length-wise, and "transverse" or crosswise, both in plane and out of plane), and end mass attitude oscillations (pitch and roll motion is called "pendulous motion," and yaw motion is just spin-around-the-tether axis).

Six control methods have been described in the literature. They are: tension variation via reel commanding; main object thrusting; deployed object thrusters; movable mass on tether; stiff tether and movable boom; aerodynamic effects. Only the first three appear practical in the early years of STS/station tethered operations.

Libration damping is done by paying out the tether when the tension is greater than usual and retrieving it at other times. This absorbs energy from the libration. In-plane libration causes large variations in tension (due to Coriolis effect), so such "yo-yo" maneuvers can damp in-plane librations quickly. Control of out-of-plane libration with this technique is more difficult. Tether oscillations can also be damped by use of this technique. Reversal of these techniques is possible so that libration can be "pumped" rather than "damped."

Although these long-period effects may dominate tethered motion when the satellite is fully or nearly extended, and special control procedures must be defined and validated, during the more dynamic phases (initial deploy and final retrieve), the time period is brief enough that such periodic effects are entirely masked by local Orbiter-specific dynamics.

7.3 TYPICAL HARDWARE

A wide variety of candidate hardware is under development for the various tethered missions now being planned. The following discussion is only meant to describe typical hardware.

7.3.1 Orbiter-Satellite Connection

The Orbiter and the tethered satellite are connected by a physical tether (section 7.3.1.1) and possibly by one or more in-line attenuation mechanisms (section 7.3.1.2).

7.3.1.1 Tether

Both conducting and nonconducting tethers are under development, selected either for pure support or for electromagnetic experimentation.

Candidate tether configurations either have no covering or have jackets of Teflon, Kevlar, or Nomex braid. Diameters range from 0.065 to 0.100 inches. The Kevlar (aramid) tether exhibits a very high strength-to-weight ratio, a wide operating range of -148° to 392° F, and good mechanical fatigue properties.

Typical tether weights run from 2 to 6 lb per kft for breaking strength of 400 to 600 lb.

An attractive material for quick satellite deployments is SPECTRA-1000. Such a tether would be 0.030 inches in diameter, weighing 0.2 lb per kft, with a 150-lb breaking strength. It melts at 300° F and has no long-term resistance to ultraviolet radiation and atomic oxygen erosion, but for short-term missions it provides 10 times the carrying capacity per line weight as does Kevlar.

Two types of tether stretch are of concern: elastic and deformable. Elastic stretch lengthens the tether under tension, but disappears under relaxation; deformable stretch is permanent alteration of line length.

Elastic stretch causes dynamic motion of the satellite, both in attitude and longitudinally along the tether. It damps out tension excursions caused by Orbiter motion (if unintentional excursions, this is a benefit; if deliberate excursions for control, this is a drawback). As a mechanism for energy storage, it can impart energy to the satellite in undesired and unexpected ways.

Deformable stretch is of concern in terms of measured length, as the tether is being retrieved. The "deployed length" parameter computed by the deployer mechanism may reach zero while a significant amount of stretched tether is still deployed. If this parameter is to be used in computations for libration control or as a cue for crew procedures, there must be a means of calibrating it against some other range determinator (e.g., radar or CCTV triangulation) and then entering a corrective offset value.

7.3.1.2 Attenuation Mechanisms

Portions of the Orbiter/satellite connector may be shock attenuation structure, either one-time (stretchable/frangible tether) or cyclic (springy tether). A property known as "lossiness" (where deformation occurs at a cost in work done) would be a useful characteristic of boom-tether-payload correction mechanisms; "lossy" structures could absorb and soften tension jerks.

7.3.2 Deploy-Only Hardware

Simple tether systems which do not envisage retrieval can pay out the tether from the deployed satellite. One such near-term system is the PMG on Hitchhiker G2. The tether is pulled out of a deployer assembly on the satellite as the satellite departs with its own momentum. Any snag will cause the tether/Orbiter attach plug to pull; at the end of the planned deploy, the plug will also nominally pull. Science data is taken only during the reel-out period.

More advanced versions of this system envisage stable stationkeeping at full tether extension. In such cases, the Orbiter/tether connection must be deliberately cut at the end of tethered operations (several REV's). Snagged tether during deploy, or deployment mechanism jam, must still result in immediate Orbiter/tether separation and a subsequent Orbiter/satellite safe separation without Orbiter maneuver.

7.3.3 Deploy/Retrieve Hardware

When tethered objects are to be deployed and then retrieved, much more complex systems are required. These can involve unfurlable boom structures, reels and motors, and corresponding monitor/control mechanisms.

7.3.3.1 Booms

For the TSS, a lattice deployment boom was chosen, rather than a telescoping or furlable design, because of inherently greater strength and damping. This is designed as a jointed non-continuous longeron boom, and is extended and retracted through a motor-driven nut at the canister outlet.

Should the boom and canister assembly need to be jettisoned from its primary support truss, pyro nuts are released and three constant-force linear spring motors give a 60-lb push over 80 inches of travel on tracks in the support truss. There is also a redundant pyro-operated tether cutter for this contingency. A tether cutter is also installed on the upper boom mechanism for simple tether guillotine.

The satellite docking cone at the top of the boom consists of a circular support covered with 0.2-in.-thick Teflon felt, and fastened to a tubular, structurally supported frame. The boom permits docking the satellite at an angle of 20°. The entire upper boom mechanism mounts on a contact ball bearing that allows $\pm 180^\circ$ rotation, powered by a gear motor, to align the aerodynamic boom for satellite reinsertion into the PLB.

7.3.3.2 Reel Motors

The TSS reel drive, which stores the tether, is powered by a brushless, 3-phase, 5-horsepower electrically-commuted samarium cobalt dc motor. The

motor operates over a dynamic range of 10 rpm to 1000 rpm at torques up to 45 ft-lb.

7.3.4 Generic Tethered Object Systems

A generic tethered object may possess a wide variety of operational capabilities, based on different types of hardware.

7.3.4.1 Line Tension Mechanisms

The most straightforward technique for maintaining short-range tether tension is for the tethered object to activate thrusters pointed down the tether. Since the plume is directly into the Orbiter payload bay, most technologies are ruled out on contamination grounds, but nitrogen gas is fully acceptable and has sufficient performance. The TSS-S has two thrusters of 2-newton force (0.45 lb) each. They are controlled over the RF link by crew inputs to a payload-specific SPEC.

Another candidate technique for maintaining satellite tension against a tether is use of another tethered object, a deployed mass at the end of a 5- to 10,000-ft tether which pulls the main payload out (like a drogue chute), and maintains tension during retrieval (fig. 7-2). Postretrieval, this mass is jettisoned. This is the so-called "space anchor."

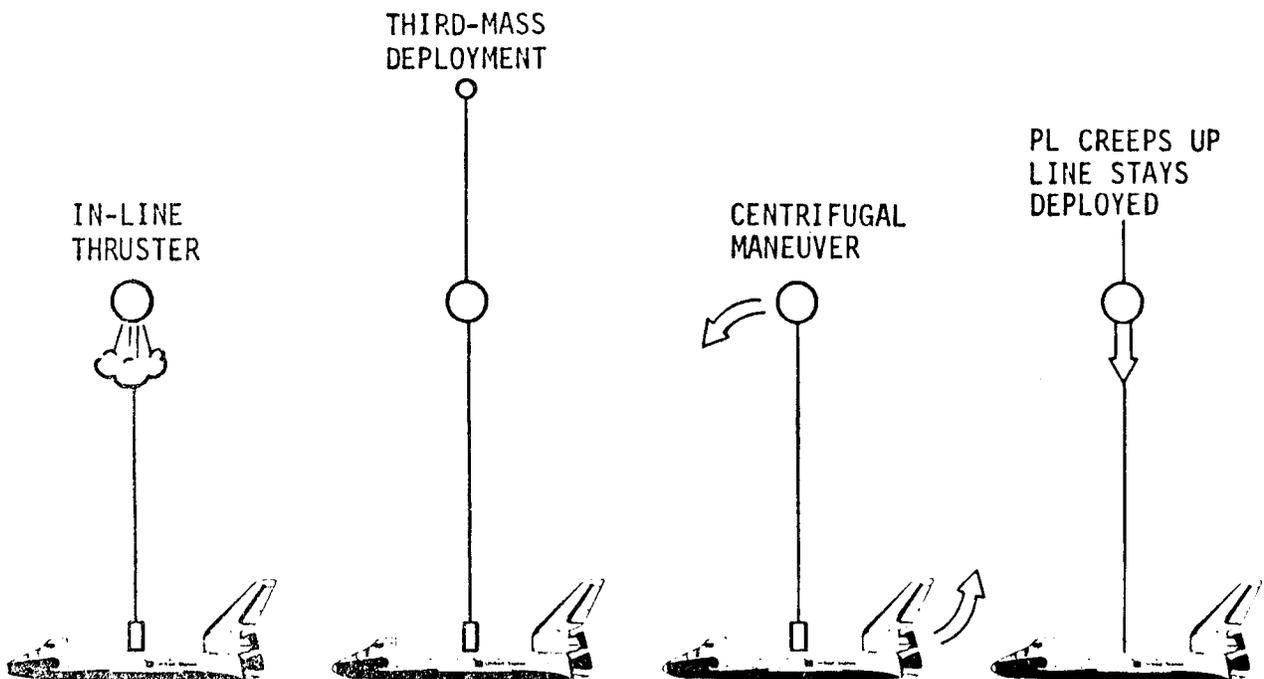


Figure 7-2.- Line-tension techniques.

7.3.4.2 Other Attitude/Translation Capability

Tension on the tether attach point on the satellite can be counted on to maintain satellite roll and pitch angles within small deadbands. However, the tether exerts no force in the satellite yaw axis (roll about the Orbiter-satellite line), so some means of active yaw control may be required both for satellite pointing and to prevent excessive tether twisting.

To assist in maintaining Orbiter-satellite relative stability, a tethered satellite may also possess translation thrusters for both in-plane (parallel to Orbiter X axis) and out-of-plane (parallel to Orbiter Y axis) maneuvers. In the event of significant satellite roll/pitch deviations, however, use of such satellite thrusters can significantly impact tether tension. While translating the satellite is a much more economical technique than translating the Orbiter, there remain operational and training concerns about the practicality of such a technique.

7.3.4.3 Radar/Optical Visibility Enhancement

Due to potential tether-induced radar degradation (in the case of electrically conducting tethers), the placement of radar enhancement devices on tethered objects may be highly desirable. If radar TRK throughout the deployed phase is deemed mandatory, use of an active transponder may be considered.

Visibility of the satellite, especially at night, may be a safety issue for close operations, especially within the range where gravity gradient forces can no longer be relied on to maintain tension. At night and with radar failed, if there are no other sensors capable of verifying safe Orbiter-satellite separation and rates, tether guillotine and Orbiter separation may be the only safe option. Hence, either high-performance reflectors or satellite-mounted lights (even long-period strobes) may be at least highly desirable.

Although volume XIV of the Payload Accommodations Document only specifies PL visibility to 1000 feet, an unresolved issue with tethered systems is whether the tether itself be considered part of the PL. If so, volume XIV lays out the requirement that the first 1000 feet of the deployed tether be visible, no matter how far out the actual satellite is. This issue must be resolved on a case-by-case basis.

Techniques to enhance visibility of the tether itself (particularly the segment closest to the satellite, for several hundred feet, either in entirety or pointwise) may be examined; such visibility may significantly enhance the ease and confidence of crew procedures during initial deploy and final retrieve operations.

7.3.4.4 Reels

Although the most common design involves a tethered satellite attached permanently to the far end of the tether, there are concepts in which the satellite itself may reel in the tether, either to store it onboard or to deploy it out the other end (i.e., the satellite "crawls" up the tether leaving it hanging free beneath it).

7.3.4.5 Grounding Device

For electro-dynamic applications, the electrical circuit must be closed by "grounding" the ends of the tether into the ionosphere, both at the Orbiter end and at the satellite end. This can be done with an electron gun or a hollow cathode.

7.3.5 Typical Tethered Payloads

A wide variety of tethered objects is already under development or advanced design. These are typical:

a. Tethered Satellite System (TSS)

The TSS is a 1100-pound, 5-ft-diameter spacecraft built by Aeritalia in Italy, under management of the Italian Council for National Research.

b. Plasma Motor-Generator (PMG)

Planned for use with the Hitchhiker G2 payload. Details TBS.
Has 200-meter tether, not retrieved.

c. Kinetic Isolation Tether Experiment (KITE)

Involves 1-ton payload (SPARTAN-class or actual modified SPARTAN spacecraft) to range of 1 to 5 kilometers (0.5 to 2.5 n. mi., or 3000 to 15,000 ft), in stable gravity-gradient attitude. In study phase only.

d. Small Expendable Deployment System (SEDS)

This demonstration experiment involves a basketball-size deployer and an 0.030-inch tether, 10 n. mi. long, weighing about 20 lb. The system is designed to deploy a payload of up to 1 to 1-1/2 tons; after deployment, the tether is jettisoned.

7.4 INTERFACE/IMPACTS TO STS

Operating a tethered object from the Orbiter can be expected to have significant impacts on many normal operating procedures, sometimes requiring major procedural changes or additions.

The primary impact of tethered objects will probably be from the enforced attitude holds required during the deployed phase; these attitudes will probably be either -Z toward or away from center of Earth. Impacts may include the following:

7.4.1 DAP

The constant torque from the tether tension can have significant impacts on attitude control, even if the Orbiter is allowed to reach an equilibrium attitude with the deployed tether. The system moments of inertia will be changed in several axes. The TSS-D torque will exert a controlling force in roll, and to a less extent in pitch, while yaw DB must also be maintained. Examination of this issue by appropriate guidance, NAV, and control analysts has not yet been undertaken.

7.4.2 Ku-Band Radar

Testing at White Sands in 1986 indicated that electrically-conducting tethers have a significant negative impact on RR TRK ability (this was anticipated on theoretical grounds). Forward scattering of the radar pulse down the tether seems to sufficiently defocus the pulse so that the return echo is weakened; the effect reduces the apparent radar cross section of the tethered object. This may have impacts for initial RR acquisition during retrieval.

7.4.3 Flight Dynamics

As a tethered satellite object is deployed to great range, the Orbiter/satellite system continues to orbit Earth in a path essentially determined by the c.m. of the whole system. However, both ground and onboard NAV will be TRK the Orbiter only, and can be offset from the true "(whole-system) Orbiter" by a significant amount. For the TSS at 20-mile range, this c.m. offset can amount to several hundred feet, which corresponds to several thousand feet downtrack error per REV. SV management must take this c.m. offset effect into account.

7.4.4 IMU Alignments

Restricted attitudes will require use of TGT's of opportunity. Further complications arise from the specific nature of the required attitude: down-deploys place the -Z STRK toward Earth and up-deploys may still have the satellite continuously in the -Z STRK FOV (at a range of 20 n. mi. the TSS-S

brightness in terms of stellar magnitude should be between 0 and -2, in daylight); in either case, the -Y STRK is pointed nearly horizontal, although there should be a narrow safe-operating range for its use. Two stars of opportunity should be available through the -Y STRK for such alignments.

7.4.5 Microgravity Effects

At maximum extension of a substantially-sized tethered object, significant microgravity acceleration will be experienced in the Orbiter in the +Z ("down") direction. The TSS at 20 n. mi. will move the Orbiter/satellite system c.g. out above the Orbiter by several hundred feet, inducing a microgravity field of several tens of microgees inside the Orbiter. While not immediately noticeable, such a field would cause any free-floating objects to "fall" to the floor within a minute or two (this may impact crew habitability), will cause all fluids to settle, and can induce convective currents in the atmosphere and other fluids (depending on differential heating). This field can last on the order of a full day, under current plans. Proper fluid feed in OMS/RCS, fuel cells, and other systems may be affected; the induced weak convective effects in the cabin atmosphere may impact cooling. As a first approximation, no serious malfunctioning might be expected since the acceleration is in the same direction as during entry and landing; however, the very long time interval of the acceleration may introduce unexpected effects. Serious systems analysis of this issue is yet to be undertaken. It should be noted that such forces already exist within the Orbiter due to its large dimensions (the crew compartment is about 50 feet from the Orbiter c.g.), but the tether-induced forces will be several times as large and in another axis.

7.5 GROUND RULES, ASSUMPTIONS, AND CONSTRAINTS

7.5.1 Dedicated Crew Size - Initial OPS

Analysis by CB indicates that four dedicated crewmembers are needed for initial dynamic tether mission phases: one MS is at the PLT station operating SPEC's; another MS is performing photodocumentation at the aft right station; the PLT is at the aft left station performing the actual flying; the CDR is at the CDR station coordinating, and preparing for contingency operations such as guillotine and separation. Conceivably, a TSS PS could also be present as an observer.

7.5.2 Dedicated Crew Size - Mature OPS

Regular tether operations, once sufficient experience has been accumulated, may be performed with three or even two dedicated crewmembers.

7.6 SPECIAL DISPLAYS/CONTROLS

Unique features of tethered operations require specially-designed monitoring tools and techniques. These can involve standard RNDZ items such as SPEC functions, CCTV systems, and cabin tools such as ranging rulers.

7.6.1 Crew Displays

During 1986 SES TSS runs, a unique pseudo-SPEC function was designed for "TSS Control," and it was arbitrarily designated "SPEC 50"; this number and the entire display definition was unique to the SES. Parameters available on the SPEC 50 display included RR range and range rate, in-plane and out-of-plane angles and angle rates, and NLOS ft/s rates, tether length and length rate (measured by the TSS-D mechanism), etc. The displayed radar range was approximately 75 feet higher than the tether length because of geometric factors. Significant insights were obtained into the desirable features of the real, still-to-be-defined "TSS Control" SPEC. Two displays, one for systems and one for dynamics, were eventually developed (fig. 7-3).

XXXX/XXX/205			TSS DYNAMICS			XX X DDD/HH:MM:SS		
						DDD/HH:MM:SS		
THRUSTER	HI	LO	IP			OP		
+X	1XS	2XS	ANG	±XXX.XXS	±XXX.XXS			
-X	3XS	4XS	RATE-	±X.XXS	±X.XXS			
+Y	5XS	6XS	VEL	±XX.XXS	±XX.XXS			
-Y	7XS	8XS	RADAR			REEL		
INLINE THRUSTERS			RNG	XXXX.XXXS	LEN	XXXX.XXXS		
+Z	1N	2N	R	±XXX.XXS	RATE	±XXX.XXS		
ON	9XS	11XS	RR	REEL	TEN	XX.XXS		
OFF	10XS	12XS	32XS		ERR	XX.XXXS		
			REF INIT	TSS ATT				
YAW CONT			INRTL	33XS	ATT	RATE		
+ROT	15XS	HOLD	LVLH	34XS	R	±XXX.XXS	±X.XXS	
-ROT	16XS	NULL	LVLH	RATE	P	±XXX.XXS	±X.XXS	
FREE			35	X.XXX	Y	±XXX.XS	±X.XXS	
19XS				TANK P			XXXXS	
VLV	OP	CL	ATT REF	VOLTS			XX.XS	
TK ISOL	20XS	21XS	INRTL	36XS				
10P	22XS	23XS	LVLH	37XS				
CDA/10P	24XS	25XS	REEL	LIGHTS			DOCK	RING
CDA/YAW	26XS	27XS	IN	38XS	ON	41XS	ROT+	43XS
IL1	28XS	29XS	OUT	39XS	OFF	42X	-	44XS
IL2	30XS	31XS	STOP	40XS	STOP			45XS
(XX)								

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Figure 7-3.- Tethered OPS control display.

CAUTION: This is not a draft SPEC and in fact may contain parameters not available for on-board display.

Enough requirements were developed to raise the issue of creating two TSS crew displays, one for TSS-S/D systems and the other devoted to TSS dynamics. The former would include a substantial body of still-undefined TSS-D parameters, as well as TSS-S systems monitoring and reel controls.

The latter would display data needed immediately at the aft crew station by the crewmember performing the flying and would be the basis for design of a generic tether dynamics SPEC for any application to tethered operations.

On the TSS DYNAMICS display, the crew should have the option of entering a length bias to correct for tether stretch during deploy; at a set range measured both by radar and by TSS-S angular size in the CCTV, the measured length should be observed, and the necessary bias consequently computed and entered.

With a correct length and length rate, time-to-berthing should be computed and displayed in MM:SS. This was simulated at the SES by setting a count-down clock based on known run duration, and it was found to be extremely useful during the terminal phase in estimating corrective firings required and in avoiding overcorrection.

TSS-S attitudes must be displayable in an Orbiter relative frame as well as LVLH, so that proper berthing alignment can be noted.

7.6.2 Special CCTV Arrangement

For 1986 SES TSS runs, a special CCTV arrangement specified that two CCTV's be placed on the TSS-D pallet, near the PLB attachment points on the right and left side. Each camera was aligned to look up past the boom tip towards the TSS-S, and the two views were multiplexed onto monitor 1 at the aft crew station to provide a pseudo-stereo representation (fig. 7-4). This technique provided superb cues to TSS-S/boom relative position and rates, especially in the final stages of the retrieval.

7.6.3 Ranging Rulers

The symmetry of the TSS-S lends itself well to use of CCTV image size subtended angle as a backup range determinator, as done on other PROX OPS missions. Traditional "ranging rulers" (which when placed over the max-zoom image of the TSS-S on the aft flight deck monitor provide a usable range indication) have been produced and utilized successfully; a special stereo ranging ruler, used to measure the center-to-center distance on the muxed view, was also tested and proved to be useful in ranges of under 200 feet. Both of these range determinator techniques are highly desirable because of nominal loss of RR range at close ranges and an unpredictable bias on the tether length measurement (as measured by the deployer mechanism) due to tether stretch during the deploy period (at final berthing, the "length" measurement may be reading negative by tens, if not hundreds of feet).

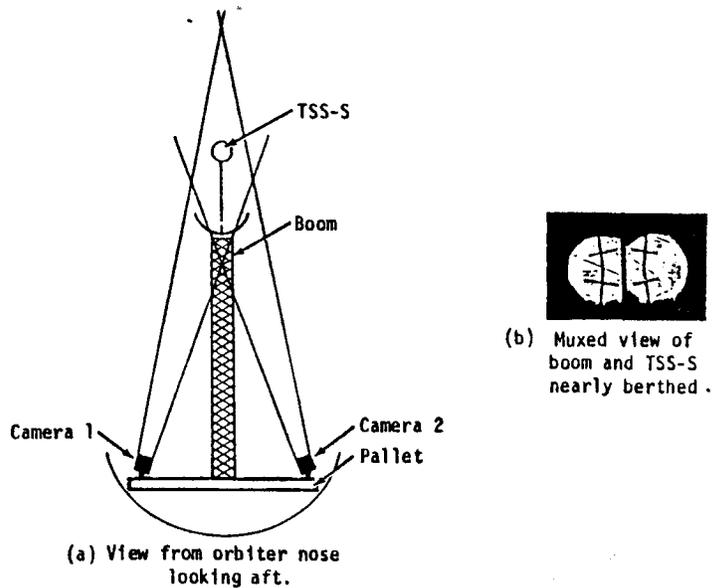


Figure 7-4.- CCTV arrangement/TSS-D boom/pallet.

7.7 CANDIDATE PROCEDURES

Early theoretical considerations and feasibility assessment have generated several candidate procedures for tethered operations. No verified procedures exist for any mission phase at this time.

7.7.1 Deploy

As discussed by Carroll (1985), there are several different theoretical deployment techniques. Two are shown in figure 7-5.

In both cases, the initial deployment is done with thrusting or a large boom.

In the first case (left), the tether is paid out under tension slightly less than the equilibrium tension level for that tether length. The tether is slightly tilted away from vertical during deployment (upper object trailing along V-BAR) and librates slightly after deployment is complete.

In the other case, after the initial near-vertical separation (to about 2 percent of the full tether length), the two end masses are allowed to drift apart in near-free-fall, with very low but controlled tension on the tether. Just under one orbit later, the tether is almost all deployed and the range rate decreases to a minimum due to orbital mechanics effects. Thrusting or tether braking is used to cushion the end of deployment and prevent end mass recoil. Then the tether system begins a large-amplitude prograde swing towards the vertical, during which high tether tension occurs.

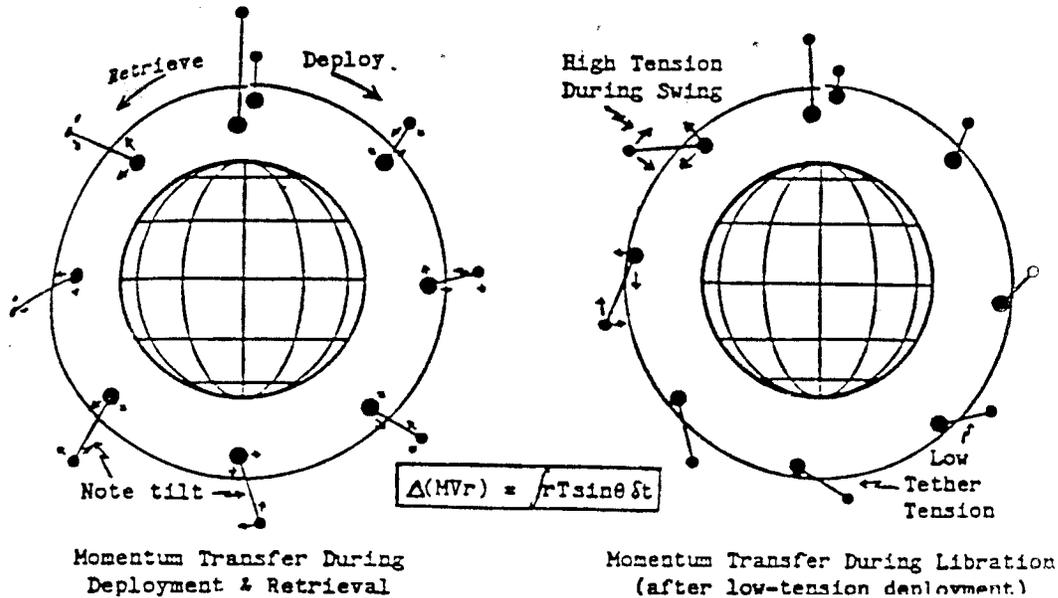


Figure 7-5.- Deployment technique

In both cases, the angular momentum transferred from one mass to the other is simply the integral over time of the radius times the horizontal component of tether tension. In one case, transfer occurs mainly during deployment; in the other case, it occurs mainly during the libration after deployment.

An intermediate strategy, deployment under moderate tension, has also been investigated. However, this technique results in very high deployment velocities and large rotating masses. It also requires powerful brakes and a more massive tether than required by the other two techniques.

Coriolis forces can cause a large bowing of the tether during deployment of light payloads. At low altitudes, aerodynamic drag can have a similar effect.

7.7.2 Stationkeeping

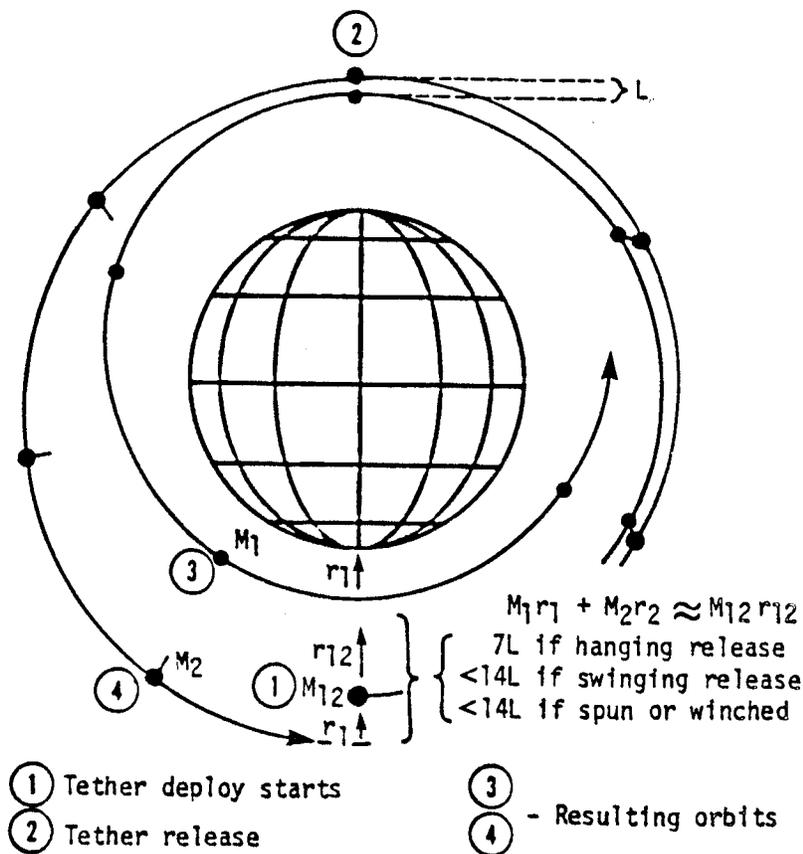
The primary control mechanism for distant tethered objects will probably be reel in/out operations, supplemented by thrusters on the object and on the Orbiter. Secondary effects can be generated by use of the moment arm provided by a long boom (such as the TSS-D).

Details remain undefined until more realistic analysis and simulations are completed.

7.7.3 Nominal Detach

Many interesting applications involve performing a hanging release of a tethered object (fig. 7-6) in order to transfer momentum from a primary body to a smaller one (resulting in transfer to a higher or lower orbit, as desired). The tether (and reel) may either be on the primary body and be retrieved for reuse or on the released body.

For two tethered objects at distance L, release of the tether causes a growing separation. After half an orbit, that separation of orbits reaches a distance of 7 times L (physical separation will be greater since the lower object will also be substantially further ahead due to orbital motion, by about 20 times L).



Effects of tether deployment and release

Figure 7-6.- Hanging release.

Under conditions of swinging release (fig. 7-7), that orbit separation can be any value less than 14 L; for spun or winched releases, it can be greater than 14 L.

Carroll (1986) gives an approximation for achievable hanging release ΔV (in LEO, with the deployed object mass much less than the main object mass) as:

$$\Delta V = k V_c \text{SQRT} (\text{tether mass} \times \text{end masses sum} / \text{end masses product})$$

where $V_c = 2300$ ft/s for Kevlar, 3300 to 3800 ft/s for advanced materials
 and $k =$ 1 for spinning operations
 1.15 for hanging releases
 1.2 for swinging releases
 1.4 for winching operations

Note that the ΔV is a function of tether mass, not length (a more massive tether can support more energetic releases). For payloads very light in comparison to launching object, the SQRT reduces to SQRT (tether mass / payload mass). For breaking strength of 10,000 pounds, Kevlar weighs 40 to 100 lb per kft, and Spectra-1000 weighs 12 to 15 lb per kft.

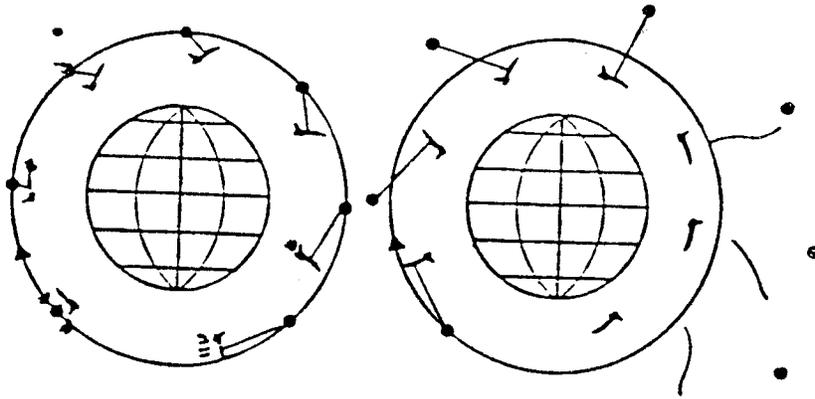


Figure 7-7.- Low-tension deployment, swing and release.

Of course, momentum given to one object is taken from another. If the momentum can later be restored by a high-efficiency propulsion system, this is tolerable. In some cases this may even be useful: if a space station uses a tether to deboost an Orbiter at the end of its resupply mission, space station orbital decay makeup needs and Orbiter deorbit burn propellant needs are both reduced.

7.7.4 Retrieve (Active)

Retrieval of tethered objects is the most difficult phase of tethered operations.

7.7.4.1 Theoretical Basis

The theoretical basis of retrieval stability contains a large, but as yet unvalidated, body of mathematical analysis.

7.7.4.2 Simulator Basis for Procedures

In 1986, a series of TSS retrievals was made on the SES, with variations in Orbiter DB's and in allowable TSS-S out-of-plane and in-plane excursions. A "best technique" was subsequently selected for follow-on contingency runs, but this cannot be construed as being any sort of standard, validated procedure. This technique is offered only as a viable candidate, which may illustrate many of the characteristics the final procedure should be expected to have.

7.7.4.3 Procedure Setup

The DAP was in LVLH, with nominal RNDZ/PROX OPS deadbands (2° NORM, 1° VERN for both DAP A,B), and small translation impulses (0.05 ft/s A, 0.01 ft/s B).

The approach was guided along a funnel with sides proportionately narrowing as tether length decreased: at 500 feet, a 5° dispersion was acceptable in either in plane or out of plane, in the 400's it was 4° , in the 300's it was 3° , and in the 200's it was 2° . The angles and rates of the satellite are observed on SPEC 50.

7.7.4.4 Initial Retrieval

Control can be accomplished by Orbiter translation, performing $\pm X$ and $\pm Y$ burns with the THC to fly the boom tip back towards the satellite image (in the case of the TSS-S, it is also possible to fly the satellite itself by use of its onboard thrusters, but this has not been thoroughly evaluated, and it may be more reasonable to make use of piloting techniques with which the crewmembers are already familiar). Small Orbiter DB's have been (not surprisingly) found to be best for allowing use of this satellite LOS as a cue to corrective maneuvering.

One significant effect of Orbiter RCS cross-coupling has been noted and deserves mention. When observing a target out the overhead window, the crewmember commands RCS translation maneuvers perpendicular to the LOS in order to control Orbiter/target relative position (in a "fly to" mode). However, because translations induce some cross-coupled rotation, the initial LOS motion of the target may be momentarily misleading. This effect is discussed in detail in section 3.8.1.2 and figure 3-44 and accentuates the need for the crewmember to be patient after performing translation pulses, to see the LOS motion after deadbanding, and not be misled by the initial LOS rates (which contain deceptive rotation-induced components). This also underlines the need for tight DB's.

To repeat, these translations are performed to keep the satellite LOS (as displayed on a SPEC) under control in the progressively narrowing funnel. Corrections must be made when the satellite LOS angles exceed the allowable limits; corrections can also be made as it passes through the zero angle(s) to null out the angle rates.

7.7.4.5 Close-in Procedure

Prior to radar losing lock inside 80 to 100 feet, the control scheme must change. Since RR angles are already becoming biased due to the geometric offset of the Ku-band antenna compared to the boom tip, and since RR lock is soon to be lost anyway, it is desirable to switch to another "fly-to" technique. Criteria for translation firings is therefore changed from RR angles to the television monitor, where the multiplexed stereo image of the boom tip is "flown to" a spot directly between the twin images of the satellite. This new piloting technique also appears to be "common sense" with easily understood criteria for corrections.

To prevent automatic deadbanding from unexpectedly disturbing the LOS, at this changeover point, DAP is moded to MAN and RPY to PULSE/PULSE/PULSE (i.e., free drift). During this final phase, the Orbiter attitudes may drift up to 5° from initial, but this should be acceptable.

A typical tension time history is shown in figure 7-8 (two examples). While the in-line thruster constant value is apparent, wide excursions also occur. This includes momentary zero-tension intervals.

7.7.4.6 Alternative Procedures

An alternate control technique during the terminal phase (defined as the close range where RR lock has broken, through contact) is to use vernier attitude control to move the boom tip. There appear to be two arguments against this technique. First, the crewmember is already accustomed to flying by translation and has become well versed in predicting LOS reactions to controllable inputs, so a new control technique would require a new period of adaptation during a very brief and dynamic phase. Secondly, since the boom probably does not extend through the Orbiter c.g., Orbiter rotations (particularly pitch) will induce substantial boom tip translations in the Z axis, complicating the piloting. For this reason, candidate procedures so far use translation control all the way through contact.

7.7.4.7 Failure-Mode Procedures

Several SES runs were made with RR failed, with VRCS failed, or with one of the two TSS-D boom pallet CCTV's failed. Prop usage more than doubled, primarily due to difficulty in correcting subtle angle rate dispersions (in sensor fail cases), or to overcorrections (in VRCS fail case). Higher tether tension excursions and longer periods of zero tension were also experienced. Nevertheless, retrievals seem to have been accomplished successfully.

7.7.4.8 Satellite-in-Motion Procedures

Pendulous motion of the satellite was another area of concern. This consists of the satellite rocking in pitch/roll from the tether attach point. We induced large pitch/roll angle rates, up to 5 to 10 deg/s (any higher, and the tether wrapped around the satellite), and noted how they quickly coupled

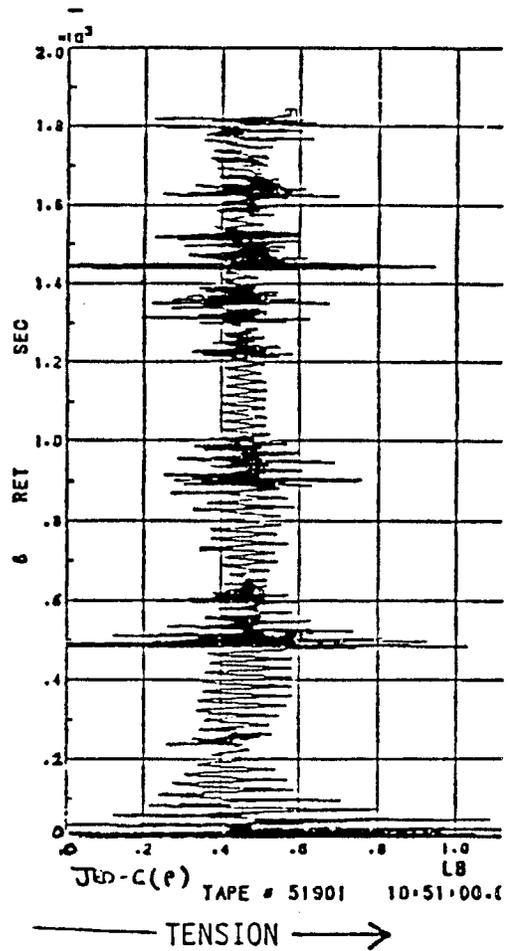
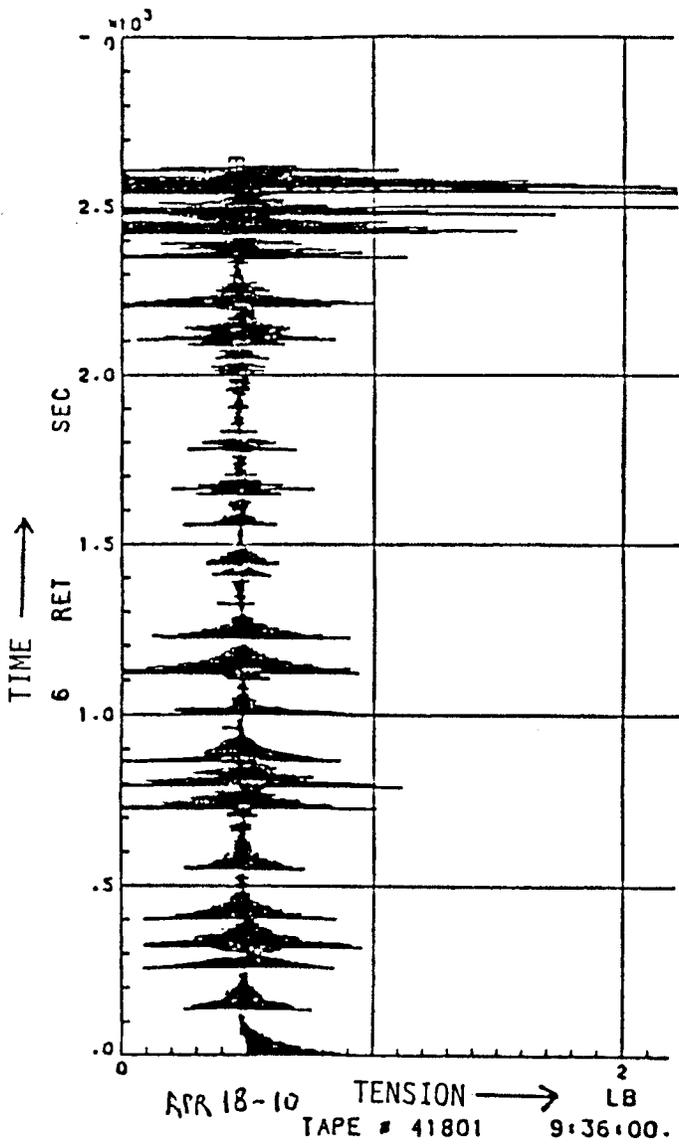


Figure 7-8.- Tension history plots with inlines, various control techniques (illustrates occurrence of zero tension).

into other axes and were continuously excited by subsequent RCS firings. While the rates never damped out, contact with boom tip was usually made well within acceptable angle ranges. Whether the contact range rate was safe could not be determined (this is a hardware issue for the deployer mechanism contractor to judge), but it did not appear to be all that much worse than in nominal cases.

7.7.5 Retrieve (Passive)

Retrieval without in-line thrusters may be performed either entirely without line tension, or with some alternate means of maintaining line tension. Both were performed on the SES in 1986, under many variations. In the absence of vigorous off-line validation, these candidate procedures must be considered very preliminary.

7.7.5.1 No-Tension Retrieval

The no-tension retrieval was performed in several variations, designed to create a known Orbiter/satellite REL position for final approach (and thus allow use of a canned preverified separation maneuver in the event of guillotine). In one, the Orbiter went to inertial hold and performed an inertial flyaround of the satellite until it reached the V-BAR (120° of orbit travel, in about 30 minutes); in another, the Orbiter went only to the satellite R-BAR, in an attempt to use gravity gradient forces to provide a small tension; in another, the approach was made in LVLH mode directly from the initial condition.

In all cases it was found possible to fly the boom tip up to the satellite while monitoring tether slack (comparing RR to tether length) and keeping it small. It was noticed that tether jerks which did occur did not seem to induce worrisome closing rates; instead, due to random satellite attitude, they mostly imparted random attitude rates to the satellite rather than inducing translations.

The major unknown in this class of procedures was how the system would respond at final boom contact. The satellite attitude was essentially random during final approach, although tether jerks tended to pull the attach point toward the center of the visible hemisphere. The SES model was of low fidelity here since it did not simulate "wrap" of the tether around the surface of the satellite; instead, the tether always ran from the attach point straight to the boom, even through the body of the satellite, if the attach point was passing across the hidden hemisphere (the "back side" of the satellite). It is conceivable that with the real hardware the satellite could nestle into the boom tip and then, through a series of final jerks as the tether continues to be reeled in, become properly aligned for latch capture (assuming no snags on satellite structure).

Even so, however, a procedure which allows tether wrap around the satellite appears to be highly undesirable. Since the satellite attitudes and rates go essentially random early in all of these scenarios, and do not appear to be controllable by any crew procedures, this option appears unacceptable.

7.7.5.2 Centrifugal Tension Procedures

The LVLH frame of reference is noninertial. The LVLH is rotating at orbital rate of 4° per minute, or 0.067 deg/s. Under initial conditions for these runs, the Orbiter is moving in a body vector $-X$ direction relative to the Orbiter/TSS system. This system rotation will generate some centrifugal force between the Orbiter and the satellite as they rotate about their mutual center of mass. This induced tension can be enhanced by deliberately creating a higher rotation rate. We chose to rotate in the $-X$ direction (versus $+X$), because we were already moving in that direction and because later control maneuvers induced less cross-coupling.

At a range of 500 to 600 feet, a $-X$ ΔV of about 0.3 ft/s is performed with THC (monitored on AVG G in SPEC 33), followed by establishment of a -0.150 deg/s pitch rate via RHC input (monitored on OPS 201 display). In the LVLH frame this was one full turn in 40 minutes. The boom tip television image is "flown to" the satellite image using VERN pitch and B NORM out-of-plane translation. DAP is manual, with ROT in DISC-PULSE-DISC (i.e., free in pitch only), and pulse sizes (deg/s) of A NORM 0.1 , B NORM 0.04 , A VERN 0.01 , B VERN 0.002 . Turning off in-line thrusters results in the tether elasticity's pulling the satellite inwards, creating a loss of tension for several minutes. However, after a series of gentle jerks, the satellite settles into a reasonable stability with a tension of 20 to 30 percent of that generated by in-line thrusters (several tension history plots are shown in figure 7-9).

If thruster fail is known at long range, and if there is manual control over the reel-in rate, the centrifugal maneuver can be initiated merely by increasing this reel-in rate, without need for thruster firing.

Since this tension is so weak, it can easily be lost entirely by small Orbiter (actually, boom tip) Z translations, even those induced by cross-couplings from translations in other axes or from rotations (translation cross-couplings or just geometric results). Thus, extremely delicate maneuvering is mandatory: pitch in A/MAN/VERN, and translate in B/MAN/NORM with 0.01 ft/s pulses. When maneuvers were made accidentally in higher rates, tension went to zero for long periods and sometimes never restabilized. Several plots of tension-versus-time are shown in figure 7-9.

Using higher rates to create stronger centrifugal force does not solve this problem. The SES reel rate model reacts badly to strong tether tension jerks by slowing or even stopping the reel-in rate. This occurs even if the average centrifugal line tension remains far below the nominal in-line thruster-induced tension, since tension spikes continuously occur due to RCS firings and these short spikes can freeze the reel-in for several seconds or longer. It is an open question whether this model is correct (are the gains simply set too low?), and if the reel-in rate is actually much more robust than a higher system spin rate might be feasible. However, in that case, other limiting factors appear.

As the satellite is reeled in during this 0.15 deg/s system spin rate, angular momentum is transferred into the Orbiter and the spin rate increases. A more important impact on the spin rate is the tendency of the satellite to pull up ($+X$) in the television field of view, requiring more $-pitch$ ("pitch up" in $-Z$ mode) to force the boom tip to chase it. This drives the pitch

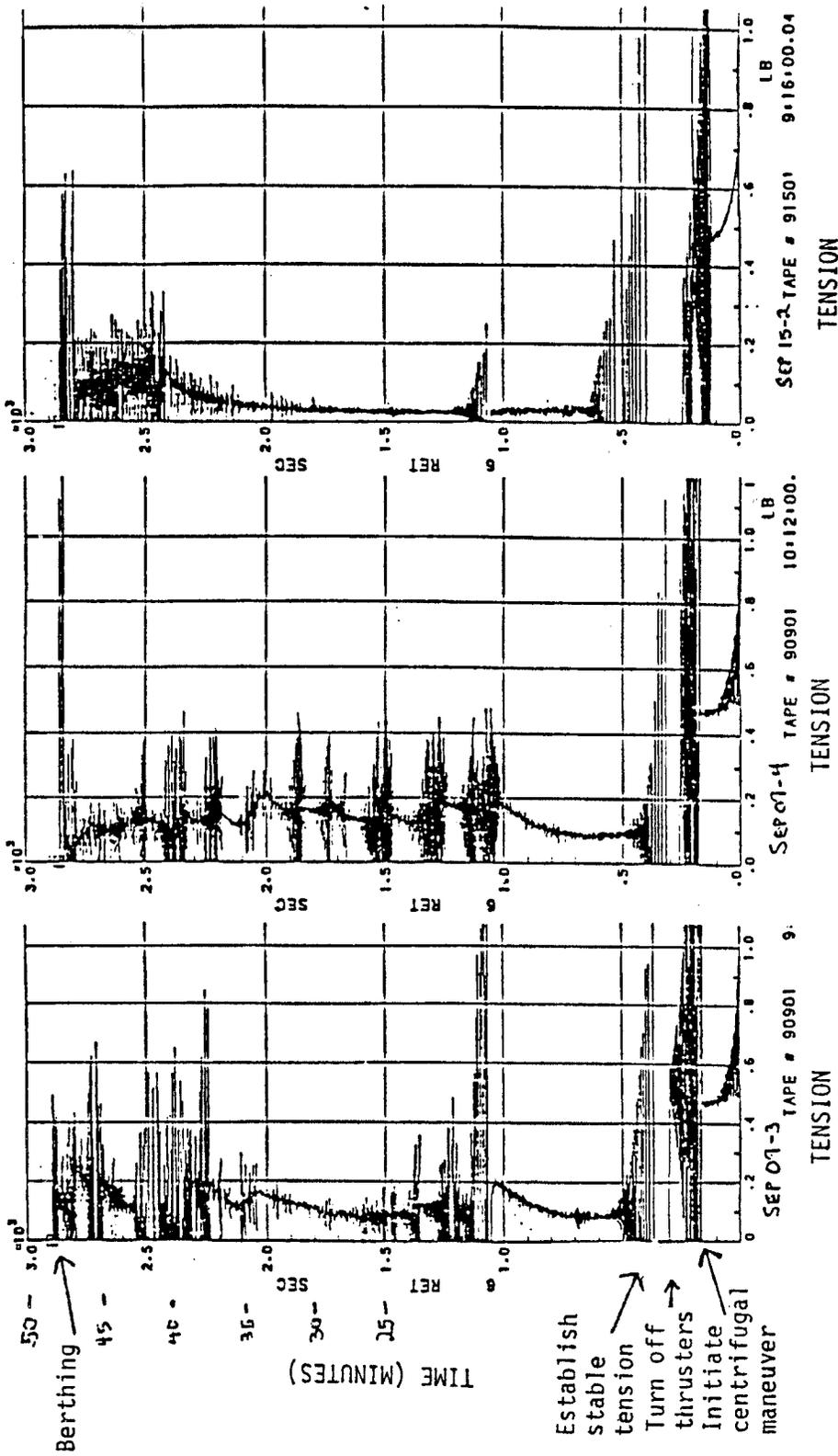


Figure 7-9.- Tension history plots. No in-lines. Centrifugal tension only.

rate from the original -0.150 deg/s to a higher rate (up to -0.400 deg/s), increasing centrifugal force and ultimately causing the satellite reel motor to jam.

To avoid this, a different "fly to" scheme must be used within about 400 feet (when tether centrifugal tension reaches about 35 percent of nominal thruster tension). This is to perform small (0.01 ft/s) +X translations, usually in bursts of 10 or 20 per minute for several minutes (the use of fewer but larger pulses does not work because of the excessive impulsive disturbances of such larger pulses on tether tension). These are sufficiently low and "pure" so as not to induce excessive pitch motion, or in any other way cause loss of the very fragile tension forces (-X pulses, it seems, are too "dirty" in terms of cross-coupling, and they do induce excessive jerks which destroy the constant non-zero tension induced by the system ROT). With such a scheme, if performed patiently and carefully, tension and length rates can both be maintained at reasonable levels throughout this interval. Care must be taken to perform these pulses randomly rather than in a regular pattern, since the longitudinal bobbing resonant frequency of a 300 to 500 foot tether would be on the order of several seconds, and it would not be good if the firings excited that motion.

Once length has dropped below 200 feet, the pitch control option can be resumed. The Orbiter, at its current rotation rate, at this point already possesses enough angular momentum that further reeling in of the satellite does not significantly add to it. These rates may climb to 0.350 to 0.400 deg/s at contact, a high but not unreasonable rate. Meanwhile, induced centrifugal tension drops as the tether length decreases.

The tension maintained constantly on the tether also maintains satellite attitudes to within proper ranges for berthing. This can be crucial to a successful retrieval. During the final few feet (as satellite body radius becomes large in proportion to remaining tether length), tension excursions become high and tension is sporadically lost; however, contact rates and attitudes appear well within acceptable ranges.

7.7.5.3 Open Issues

This passive centrifugal retrieval technique requires substantially more study, both in simulators and analytically. What are visibility considerations (for example, the Sun crossing the FOV at least once)? What are control impacts of finishing retrieval with a pitch rate as high as half a deg/s? What kind of separation maneuvers can be validated for use if a guillotine is required from a random Orbiter/TSS-S pitch orientation? How can this retrieval mode be initiated from any arbitrary range, since the in-line thrusters may fail at any range? These questions were uncovered by the current effort (answers will take substantially more effort); it is prudent to assume that additional questions await discovery.

In conclusion, initial feasibility assessment does suggest that this centrifugal procedure is a viable candidate for consideration in the no-thrusters contingency case, but it can in no way be considered verified since unconsidered factors (or different models) may provide hidden showstoppers.

7.7.6 Reel Stop/Start

The 1986 TSS SES runs indicated that there may be serious problems associated with reel motor brake/jam/lock cases. The TSS-S possesses yaw control thrusters (roll about the axis of the tether), and has $\pm X$ and $\pm Y$ translation thrusters (they work well on the SES; we found no surprises) but it has no roll/pitch attitude control. As long as there is tension on the tether, restoring torques are generated against all roll or pitch dispersions. This feature, this lack of positive roll/pitch attitude control, severely impacted the passive no-tension techniques described above since it led to random satellite attitudes and consequently probable tether wrap; for the motor stop case, it is even worse.

The problem is this: the TSS-S has its initial approach rate of several tenths of a foot per second, and only the weak in-line thruster is repelling it from the Orbiter. From several runs and from back-of-envelope calculations, it is clear that even after reel lock the TSS-S will continue inward (toward the Orbiter) from 20 to 40 seconds, then come to a stop, then fall back out (accelerated by the in-line thrusters) and suddenly run into a jerk when the tether goes taut. At this point, small attitude dispersions which are always present will be translated by the attach-point jerk (a moment arm offset from the satellite c.g.) into roll/pitch rates of up to several deg/s. Even if the rates are low after this first jerk, the second jerk a minute or so later drives them out of control; usually one jerk is enough. Within a minute, the tether is wrapping around the TSS-S.

This could possibly be avoided if the motor stop were extended over a long period of time, say 30 to 60 seconds, while the weak in-line thrusters maintain tension. However, under the current design the reel brake will probably bring the reel to full stop within 5 to 10 seconds, and the TSS-S will then surge upwards in free-flight before falling back against its tether and going into an uncontrolled tumble. Guillotine follows.

[Intuitively there may also be problems with where the slack tether collects during this particular sequence. When the reel-in ceases, the TSS-S and tether will continue towards the Orbiter under their own momentum, and the excess tether immediately above the TSS-D boom may collect at the boom tip and even spill over. The boom is high enough to prevent contact within the PLB unless the slack amounts to more than 100 feet; however, snagging on the outside of the boom tip may occur, especially if the slackened tether forms loops.]

A wide variation of techniques was tried to counter this disastrous consequence of engaging the reel brake. The in-line thruster was cycled on and off to force the TSS-S back against a taut tether; Orbiter +Z translations were used to reduce slack, and -Z translations were made to soften the full-length tautness jerk; centrifugal forces were induced by system ROT's to try to push the bouncing TSS-S against a taut tether. None worked; in all cases, each jerk pulled the TSS-S back inwards in preparation for a subsequent jerk, and no sign of TSS-S angle excursion damping could be detected. This was most likely because the greatest force of the jerks came from the high random attitude rates (which never damped), with random disturbances from variations in absolute Orbiter/TSS-S range.

Even at system spin rates of up to 1.0 deg/s, the bouncing would not damp out. The bouncing was controllable in that the satellite appeared to be bouncing around the radius of the tether, never approaching more than 10 to 20 feet from full extension (and thus not threatening to contact the Orbiter). But TSS-S attitudes were out of control, and tether wrap was almost certainly unavoidable. By the criterion of safe TSS-D retrieval, this situation was absolutely unacceptable and guillotine would be mandatory.

An attempt to spin-stabilize the TSS-S by deliberately inducing a yaw rate in it also seems to be ineffective. Hopefully this would have restrained pitch/yaw excursions and allow the bouncing to damp out. However, the control system as modeled only allowed a ± 5 deg/s rate and this was not enough: angle rates quickly became just as bad as with no "spin-stabilization." Perhaps a TSS-S yaw (spin) rate of 20 to 30 deg/s would be more effective, but it may not be achievable with current TSS control laws. Also, fluid damping in the satellite (e.g., vanes in the N2 tank) may promise sufficient stability.

If the fall-back jerk is not too strong (either at a close range when the closing rate is low, or if the Orbiter performs some -Z in anticipation of the tether going taut), then some control scheme may be effective. Although we were never successful in several runs (some up to a full orbit in duration) in establishing stability (defined as continuous non-zero tension and attach point remaining on visible hemisphere of TSS-S), we cannot rule out the possibility that some technique may be developed. Nevertheless, it looks unlikely.

The implications of this discovery seem to be that it is unacceptable to brake the reel at all, at least during retrievals and at the close ranges we were examining. Any situation requiring braking the reel should be serious enough to accept consequent TSS-S guillotine. This is an extremely severe constraint and needs to be widely discussed in the dynamics and operations groups. Preliminary analysis has suggested that merely unpowering the motor would allow a sufficiently gentle stop for tension to be maintained.

Furthermore, planning must anticipate an unintentional reel jam at ANY range, with subsequent loss of TSS-S attitude control. Procedures must be developed to accommodate such failure modes.

7.7.7 Jettison/Separation

In the tether guillotine case, two features were accentuated. First, the TSS-S becomes a free-flier with an initial closing rate, and secondly, if the in-line thrusters are still firing, they begin to impart an unpredictable ΔV to the TSS-S as the attitude of the satellite wanders out of control. Neither of these features is at all comforting. A prompt and powerful (1 ft/s) Orbiter +Z separation seemed called for (alternately, a strong TSS-S X/Y translation may be initiated before guillotining). Much more PROX OPS and separation analysis and simulations are required here before we can be comfortable about having a reliable procedure.

7.7.8 RNDZ With Tethered Object

Deleted

7.7.9 Loose Tether

7.7.9.1 Jettisoned From Orbiter

Due to the low mass-to-area ratio of typical tether materials, in LEO the tether should depart from the Orbiter extremely rapidly due to differential drag. Natural drag effects dominate all reasonable Orbiter ΔV maneuvers except at very low range.

7.7.9.2 Broken Tether

A loose tether attached to the Orbiter, especially one with a closing velocity induced by continued reel-in (and to a lesser degree by suddenly-released tension), must be of operational concern due to the potential for structural contact.

At very long ranges (> several miles), analysis indicates that differential drag and gravity gradient effects should overcome all reasonable initial closing rates and pull the tether out away from the Orbiter, restoring tautness in a safe and stable configuration.

At medium ranges (1000 feet to several miles) the tether momentum would probably carry it back toward the Orbiter. However, for reasonable return times (several minutes) and stable initial conditions (typical of known deployment/retrieval scenarios), the main segment of the tether will be carried down the V-BAR by Coriolis forces, sufficient to assure Orbiter structure avoidance. If the Orbiter end of the tether is cut in a reasonable reaction time (3 to 5 minutes), the tether segment in this case will entirely miss the Orbiter.

At short ranges (less than 1000 feet from Orbiter to break point) the tether will probably recontact the Orbiter at a speed of 10 to 20 ft/s. Time from break to recontact is on the order of 1 minute.

Since the tether segment is short and light, RCS plume ward-off techniques (perform +Z translation, fly away from tether) appear promising in this case. The technique seems to have the advantage of not being harmful in the event a break is perceived, but does not in fact exist; taking such precautionary steps can be done without impacting successful tethered operations. The tether would become taut again quickly.

7.8 Open Issues

Through use of the excellent SES model in the 1986 studies, significant new insights into the TSS-S terminal phase retrieval process were gained. Although no operational procedures have yet been designed, much less

verified, nevertheless, a number of promising candidate techniques were made available as a starting point for downstream procedures development work. Deployment jam can cause high stresses and recoil velocities. One proposed fix is to add a section of yieldable tether material which might prevent a fast recoil in this eventuality.

A severed thruster could recoil and foul Orbiter mechanisms. Can the RCS thrusters be used to blow away or deflect a recoiling tether (at low recoil velocities) before it piles up around the Orbiter?

SECTION 8 ADVANCED RENDEZVOUS OPERATIONS

Future rendezvous missions will employ standardized procedures as described in sections 4 and 5, as well as as-yet undeveloped procedures made necessary by new hardware, operating constraints, and capabilities. This section is intended to serve as an introduction to these new procedures and to the groundrules, assumptions, and constraints under which these procedures are being developed.

Because of the rapid evolution of such features, it is anticipated that this section will be replaced by new editions at approximate 2-year intervals indefinitely. As any particular subset of procedures matures, it will be incorporated into a more static chapter.

8.1 MANEUVERABLE FREE-FLIERS

Certain types of deployable/retrievable payloads have their own propulsion systems.

8.1.1 General NASA Policy

Standard orbits are defined as:

- Deployment in 28.45° inclination, 160 n. mi altitude
- Retrieval from same inclination, 170 n. mi altitude

8.1.2 Mission Profile

Spacecraft is expected to boost to higher altitude (typically 200 to 300 n. mi.) and then back to 170 n. mi. for pickup. The minimum time between deploy and retrieve is 6 months, which sufficiently decouples the two STS missions. If retrieval does not occur, reflight will occur within 6 to 9 months; spacecraft would reboost to achieve required orbit lifetime.

The spacecraft position within the plane of retrieval will be specified by the NSTS. It requires the spacecraft to perform a gross rendezvous of its own with a "ghost target" prior to Orbiter arrival; required accuracy is defined by a region around the ghost target known as the "control box," whose exact size and shape are currently under development. Placement of this control box will be defined in preliminary form for mission planning, then defined better shortly after deployment. It will then be updated 30 days prior to retrieval launch, and finally defined more precisely shortly after retrieval launch.

A "go-for-descent" will be given to the retrieval customer within the first few hours of the Orbiter launch. The spacecraft must then descend into the control box within 48 hours.

8.1.3 Rendezvous Operations

Initial Orbiter rendezvous maneuvers will commence prior to actual arrival of target in the control box. Hence, initial rendezvous burns may be targeted against an empty spot. NSTS requirements are for spacecraft to occupy that spot at least (but perhaps not much more than) 15 hours prior to rendezvous, in time for ground tracking and STS phasing prior to the crew sleep period on the night before rendezvous.

Note: A ground-up rendezvous begins at lift-off for phasing control and yaw steering for plane control; under these conditions, OMS-2 is usually targeted as an NC burn.

8.2 OMV OPERATIONS

8.2.1 Guidelines and Constraints

Orbiter and OMV rendezvous capabilities must be integrated to develop a successful rendezvous technique. A single rendezvous trajectory should be used to support nominal and contingency operations, satisfying all safety and operational aspects of an approach to a manned vehicle. The rationale for this is

- a. To minimize impacts to manned vehicle planned timelines.
- b. To allow OMV profile design (for ranges <20 n. mi.) to accommodate Orbiter backup rendezvous procedures, so that the profile is monitorable by the Orbiter (the Orbiter may attempt a "mirror image" rendezvous, if required). Orbiter capabilities and techniques affect OMV profile design.
- c. To maintain commonality. The profile design for the OMV/PL should be the same as OMV/Orbiter, to utilize common engineering studies and similar crew procedures and training.

8.2.2 Requirements

Each vehicle must be capable of being monitored by the other to maximize safety and mission success. This is because each vehicle can potentially back up the other by switching from a passive target mode to an active chaser mode.

To allow this option, each vehicle must maintain an accurate relative state vector knowledge at all times, both for target-to-chaser handover and for

breakout initiation. Orbiter Ku-band radar data may be sent to the OMV to support OMV radar fail; OMV radar data will be sent to the Orbiter to support Orbiter RR fail (this transmission can be via the MCC). The Orbiter will be executing attitude maneuvers to maintain OMV LOS, and relative state sensing is required.

Additionally, appropriate visual tracking aids should be provided on both vehicles (e.g., OMV running lights and STS docking lights). The OMV needs to have redundant CCTV systems.

8.2.3 Candidate Rendezvous Procedures

The OMV will be piloted from a control console in or near the Flight Dynamics MPSR in the JSC STS MCC. RNDZ/PROX OPS profiles and procedures, as well as the control console itself, will be developed by JSC-DM43, which will also provide real-time support for this function.

8.2.4 Candidate Proximity Operations Procedures

The OMV will be involved in proximity operations with manned vehicles (Orbiter and SS), and its design must safely support these operations. For the SS, this will involve all sortie missions, with SS control within the Command and Control Zone (about 20 n. mi.) including activity at grapple ranges. For the Orbiter, this will involve all rendezvous operations (after initial verification phase) to within 1000 feet on the V-BAR. This is because the lighter vehicle uses less propellant, and the OMV's use of GPS/radar allows better navigation, quicker relative state convergence after a burn, and consequently, tighter trajectory control. However, a quick Orbiter response is required if OMV failures are detected, either to complete the rendezvous or perform breakout.

8.3 MMU OPERATIONS

The frequent use of one or more MMU's by crewmembers in the vicinity of the Orbiter, or the SS, is expected. These operations have PROX OPS implications, and PROX OPS considerations affect the design of MMU flight procedures.

8.3.1 Nominal MMU Operations

TBD

8.3.2 Nominal Three-Body Operations

TBD

8.3.3 MMU Contingency Rescue Operations

MMU rescue procedures using the Orbiter were developed in support of STS-11, STS 41-C, and STS 51-A. Although straightforward in concept, the rescue can become difficult and expensive if a third body (e.g., a satellite to be retrieved) is involved, or if an inertial approach or inertial station-keeping has been used. Range and range rate data may be lacking, since flight experience (STS-11) has shown that the RR has had difficulty locking on to an MMU crewmember. In general, the rescue should be done by Orbiter translation commands only, reserving the RHC for use only if the MMU is not visible out the overhead window. This is because the pilot needs to maintain a visual reference with the horizon, with the aft ADI (in LVLH) defining the orbit plane. Rescue is completed by scooping the MMU into the PLB at a range rate of about 0.2 ft/s or less, so that the crewmember can easily grab something, or be grabbed by another crewmember without injury or PLB damage.

8.4 SPACE STATION OPERATIONS

8.4.1 Zones

TBD

8.4.2 Impact on Current Sensors

8.4.2.1 Star Tracker

TBD

8.4.2.2 CCTV

TBS

8.4.2.3 Radar

Due to structural size, the SS ceases to be a point target at a range of several miles. Considering maximum RR track range, the SS may NEVER be a point target.

When the range is less than 2 n. mi., angle data will be in error if the RR is in an angle tracking mode, such as the GPC or AUTO TRK. In these modes, the angle tracking is accomplished by a closed loop system in which the antenna is slewed in accordance with the strength of the return signal. Thus, as the RR begins to look off one end of the SS truss, the return signal strength will drop, and this will in turn command the antenna to move back down the truss. Thus, the angle tracking mode will cause the RR LOS to

wander. Beam wander can (and is likely to) render angle rate data useless. If incorporated into NAV, this poor data could lead to a poor MC4 solution, and perhaps even a degraded MC3 solution.

R-DOT is unaffected. This is due to the fact that doppler range rate is unaffected by the angle wander of the radar. Range, however, could be in error. This will not be significant for range greater than a couple thousand feet.

Acquisition performance can be degraded since a large return with rapid fluctuation can inhibit sidelobe rejection logic. Radar target enhancement devices such as a passive reflector or a transponder are desirable, but will likely not be developed due to cost.

For the radar fail case, ground analysis and simulation provide a high degree of confidence in a successful rendezvous and final approach to the SS using the current Orbiter radar fail procedures, given the following assumptions:

- A well-trained crew
- No other Orbiter systems problems
- Adequate propellant

The piloting task in a radar fail trajectory could be facilitated by the use of a PROX OPS sensor which would supply range and range rate data. Although the pilot will still face the task of LOS control, the R and R-DOT data will aid him in his braking gates, which will result in propellant savings and lower plume impingement. A preliminary (1986) study indicated that the piloting task in a radar fail trajectory could be further improved by executing a targeted midcourse burn using the data from a PROX OPS sensor, assuming it had a useful range of at least 2 n. mi., and that the quality of its data is comparable to that of the RR. This midcourse burn will adjust the trajectory such that the resulting LOS rates in manual phase are small, which will reduce the pilot's workload and save propellant.

8.4.3 Future Sensors

8.4.3.1 Laser Docking Sensor (LDS)

The laser docking sensor (LDS) has a current design specification to track a target out to a range of 1 kilometer (3300 feet, or about one-half n. mi.). With this range, it would provide valuable range and rate data during manual phase and approach portions of the rendezvous. It would complement RR, and in event of RR failure, become primary range/rate source for piloting the Orbiter during the manual phase.

Potential extensions of LDS range would greatly facilitate rendezvous during radar fail cases. If LDS range were extended to 2 n. mi., it could be used

for MC4 targeting. In "short" cases, this results in significant fuel savings and an easier piloting task (versus non-sensor RR-fail techniques); in "long" cases, this results in some propellant savings and also a much easier piloting task.

The DM43 position is that an LDS with the capability of sending its data into REL NAV should be baselined. The rationale for this position is that without an LDS, the primary source of R-DOT data during the docking phase (the last 50 feet of which are critical) defaults to the ranging rulers, which are inaccurate, slow, difficult to use, and were intended only as a backup to the RR in the event it failed. The ranging rulers depend on the CCTV system, which in-flight experience has shown to be unreliable and marginal for use as any type of ranging aid. This implies that there would be no reasonable backup to the ranging rulers, which would utilize the CCTV on the docking module during docking operations. In summary, the failure of a single CCTV would leave the Orbiter with no reliable R/R-DOT data whatsoever, and without any reasonable backup.

8.4.3.2 Transponder

The current STS RR operates only in PASSIVE ("skin track") mode but the option exists to select COOP mode (target-mounted transponder), and current hardware/software does support that mode. The active mode of operations has not been certified, hence it's ability to meet the Orbiter Vehicle End Item (OVEI) specification performance requirement is unknown. Hardware modifications and additional testing of the Ku system would be necessary to meet the OVEI specification. If there were a payload existing today that had a transponder, and if COOP operations were attempted, experts are "fairly confident" that the target would be acquired. Some of the firmware (2 or 3 PROMS) in the electronics assembly (EA) would need to be changed to improve system performance enough to bring it up to spec. Changes to the GPC flight software would not be required.

8.4.4 Docking Operations

A working definition of "docking" (as opposed to "grappling" and/or "berthing") involves the much larger sizes of spacecraft which must be docked. Additionally, "docking" usually implies a specialized docking mechanism with a pressurized internal tunnel for CREW TRANSFER.

The Orbiter may be expected to dock with a variety of orbiting objects in the future. These include not only the NASA SS but also the Industrial Space Facility (ISF), various large free-fliers, and international (non-U.S.) spacecraft.

Although it is not yet known whether RMS berthing or direct docking will be chosen as the primary method of mating the SS with the Orbiter, it is clear that manual docking procedures must be developed, if only for use as a backup in the event of RMS failure. JSC-DM43 has made numerous docking runs in simulators, using a variety of techniques and sensor combinations. While

to date the studies have been preliminary in nature, it has been found that a conventional V-BAR approach to the dual keel SS configuration, using the LDS, seems to work best. Low Z mode is used until a range of 200 to 300 feet from the docking port is reached, then NORM Z is selected to protect the upper and lower trusses (assuming dual keel configuration) from plume effects. A relatively "loose" approach is flown, with the pilot not actively attempting to center the docking target in the COAS until a range of about 50 feet is reached, although it should be kept within about 2° of center during this phase. An R-DOT of about -0.2 ft/s is comfortable up to 50 feet, at which time the pilot begins "nibbling" at the R-DOT to achieve about -0.1 ft/s by a 20-foot range. Between 50 and 20 feet, he "flies down the funnel" to actively get the target centered by the 20-foot point. From this point on, the pilot must aggressively manage the LOS situation while a second crewmember calls out the range and range rate. Standard PROX OPS DAP settings are used for translation and attitude control. If near the PRCS ATT DB while translating, it is usually best to let the PRCS fire rather than having the VRCS possibly start a discrete rate maneuver. Inside of about 10 feet, both crewmembers are very busy, with the pilot flying exclusively out-the-window, and the second crewmember calling out range and range rate at half-foot intervals, while monitoring deadbanding and watching for major R-DOT excursions due to cross-coupling effects. The R-DOT goal at docking is -0.05 to -0.10 ft/s, with -0.2 ft/s thought to be the maximum allowable. This R-DOT is not difficult to achieve, and very few runs exceeded -0.15 ft/s.

If, on the other hand, the goal is to grapple the SS, one needs only to null out this last remaining R-DOT so that the RMS operator can perform grapple in the conventional manner (see section 4). Nulling these residual rates causes only a tiny marginal increase in contamination (compared with not nulling rates), while greatly increasing safety margins. This is because loads on the RMS will be far lower if the relative rate goal is zero, and we are much less vulnerable to the consequences of RMS failures at critical moments if we are not depending on it to take out these final rates. Further, the RMS is not certified to handle payloads exceeding 65,000 lbm. Finally, if rates are nulled, the RMS operator can make a "relaxed" grapple attempt, rather than worrying about what happens if he misses the grapple fixture while trying to "grab it on the fly".

8.4.4.1 RCS Issues

If the VRCS is failed, SES experience has shown that using a PRCS ATT DB of 1° is probably the best workaround. Although a docking is doable under these conditions, it is a bit "sporty." R-DOT can take some wild swings, even reversals, due to cross-coupling. LOS control is very difficult, and the pilot must be prepared for a "missed approach" inside 5 feet. In such a case, he should establish a positive opening rate of about 0.05 ft/s, get out to about 5 to 10 feet, let things settle down, and try again. The LDS really proves its value here, giving instantaneous range and range rate data which is critical to have and impossible to achieve by any other method.

8.4.4.2 Mechanical Systems

TBD

8.4.4.3 Other Orbiter Systems Issues

TBD

8.4.5 Orbiter Procedures

8.4.5.1 Ground-up Rendezvous

TBD

8.4.5.2 PROX OPS (SS Assembly)

TBD

8.4.5.3 Separation

Candidate separation procedures are under study. One candidate involves free drift at the moment of undocking, with a 0.05 to 0.10 ft/s posigrade burn, then command tail-to-Earth pointing. Followed 1 to 5 minutes later by about 0.2 to 0.5 ft/s radial down, the Orbiter achieves a position on the +V-BAR of about 1000 to 1300 feet after about 30 minutes. From there, several options for final separation exist. An alternative trajectory to this is a simple posigrade burn of 0.3 to 0.5 ft/s, which should give good clearance over the upper truss.

8.4.5.4 Visit To Outlying Free-Flier

TBD

8.4.5.5 Contingency

TBD

8.4.6 Non-Shuttle Rendezvous/PROX OPS

TBD

8.5 NON-LEO OPERATIONS

TBD

8.5.1 GEO Rendezvous

TBD

8.5.2 Low Lunar Orbit Rendezvous

TBD

8.5.3 Earth-Moon L-Z Rendezvous

TBD

8.5.4 Deep Space Rendezvous

TBD

8.5.5 Planetary Orbit Rendezvous

TBD

8.5.6 Planetary Surface Rendezvous

TBD

APPENDIX A
STS RENDEZVOUS/PROX OPS EXPERIENCE

Over the course of several years a wide variety of RNDZ and PROX OPS experience has been accumulated. General material has already been incorporated into the body of this handbook, but a mission-specific enumeration of "lessons learned" is presented in a separate RSOC report, "STS RNDZ & PROX OPS EXPERIENCE."

RNDZ/PROX OPS missions to date are summarized in table A-I. These include missions for which planning was done, but which were cancelled.

The material in this section has been extracted from flight crew reports, from technical reports, from FDF Rendezvous and Prox Ops books, and from DM43 archives.

TABLE A-1.- STS RENDEZVOUS/PROX OPS MISSIONS

Mission	Launch date	Activities
STS-7	1983 June 18	SPAS-01 PROX OPS
STS-10	1983 Nov.	IRT - mission cancelled
STS 41-B	1984 Feb. 03	IRT practice TRK
STS 41-C	1984 Apr. 06	LDEF deploy; SMM RNDZ (twice)
STS 41-F	1984 Aug.	Spartan - mission cancelled
STS 51-A	1984 Nov. 08	Palapa/Weststar RNDZ /recovery
STS 51-D	1985 Apr.	LDEF retrieve - cancelled
STS 51-DR	1985 Apr. 12	Syncom contingency RNDZ
STS 51-G	1985 June 17	Spartan-1 deploy/retrieve
STS 51-F	1985 July 29	PDP PROX OPS
STS 51-I	1985 Aug. 27	Syncom RNDZ/repair
STS 61-B	1985 Nov. 27	OEX DAP test
STS 51-L	1986 Jan. 28	Spartan Halley
STS 61-J	1986	HST rendezvous: cancelled

APPENDIX B
GLOSSARY

Precise use of terminology is crucial to avoid confusion during time-critical rendezvous and proximity operations. The following discussions are intended to allow differentiation between potentially confusing or ambiguous terms.

- A. The difference between "Rendezvous Operations" and "Proximity Operations" is as follows:

Rendezvous operations (RNDZ OPS) are defined to include all Orbiter rendezvous maneuvers and associated rendezvous activities terminating with the initiation of PROX OPS. Rendezvous operations use closed loop guidance, navigation, and control to achieve a desired relative state.

Proximity operations (PROX OPS) begin at completion of RNDZ OPS when the Orbiter range to target is less than 1000 feet and the LVLH relative velocity is less than 1 ft/s in each axis. Proximity operations utilize crew visual observations and piloting techniques to achieve a desired relative state.

- B. Ti versus T1: Rendezvous operations involve two similar terms, "Ti" (tee-eye) and "T1" (tee-wun), which have obvious potential for confusion and ambiguity on unclear documentation or during fast-breaking flight operations. A long history and voluminous literature make changing either term impractical and highly unlikely. However, a full appreciation of their precise meanings and usages can help in avoiding such potentially harmful ambiguity. Formerly, Ti was written "TI"; the change was made in 1986 to help differentiate the terms in written form.

Ti - This is a specific rendezvous maneuver, the transition initiation, which is the first burn aimed to intercept the target position. Any discussion of the actual onboard rendezvous maneuver sequence can involve reference to "Ti". "Transition phase" is the phase from Ti (transition initiation) through assumption of manual control (MC4 + 2 min, or sunrise, in a radar fail case), at which point "terminal phase" (or "manual phase") begins.

T1 - This is the first of a pair of maneuvers (T1 and T2) to be targeted by the ORB TGT function; it stands for "time-1," and refers to the first maneuver of a two-impulse sequence. The first maneuver (T1) is executed at time-1 and is targeted to intercept a point in space relative to the target at a future time, T2. The T2 maneuver is one that is executed if, and only if, it is desired to null relative rates at the T2 offset point. Since the nulling maneuver is not performed in any current rendezvous procedures, a T2 maneuver is never computed.

Note: When performing targeting for Ti, there can be reference to a "Ti T1".

- C. Breakout, bailout, and backout: "Breakout" is the only proper term for the maneuver executed to abort the rendezvous/PROX OPS phase ("Bailout" is obsolete and thus unacceptable.) "Backout", or "PROX OPS Backout," is the term for separating to beyond 200 feet due to flight rules regarding loss of defined capabilities. It implies a translation to 200 feet, then stationkeeping at that range until the approach can be resumed or until breakout.
- D. "On time": The MC2 burn is normally executed "on elevation angle," as computed by ORB TGT'ing. However, if the TIG slip exceeds the prescribed interval (i.e., falls outside the time limits), the burn is executed at the "hardstop" time, or "on time" (as opposed to nominal "on elevation"), and another target set must be called up. Be aware that to the outside world, executing a burn "on time" means not doing it late or early, but on the time expected (i.e., the preflight MC2 TIG), which is NOT what we mean in this case.
- E. "OPS mode recall" is used by DPS to describe an unambiguous process, but for rendezvous it matters why the recall is being performed: if it is merely to restring, there is no impact; if it is to add a GPC to the redundant set, there is a brief but unavoidable transition to OPS 0 which most certainly does impact REL NAV (see section 6). The purpose of the OPS mode recall is thus required in order to understand its impact. There are two tabs in the RNDZ Book (RNDZ NAV SAFING and RECOVERY) which give detailed crew actions when moving a GPC into or out of the redundant set, and for OPS transitions (G2 to G8 or G3).
- F. The terms "execute" and "perform" are both used with rendezvous maneuvers, but they are not synonymous. In general, a procedural sequence (such as a particular block) is "performed" step by step, while a specific translation maneuver is "executed," as when the "EXEC" indication flashes on ORB MNVR EXEC to arm the execution of the prescribed burn. This is a subtle distinction; and no ambiguity results when the two terms happen to be used interchangeably.
- G. The acronym "MNVR" should be utilized as an abbreviation of the word "maneuver" only in specific situations. These involve the execution of a specific translation maneuver, as in "ORB MNVR EXEC"; the acronym may also be used to refer to that specific delta-V burn. "MNVR" should not be used as an abbreviation of any attitude maneuver or to refer to a sequence of maneuvers which are performed as an integrated procedure. The exception is the maneuver to BURN ATT in MM 202, where ITEM 27 is labeled MNVR. This is awkward and potentially confusing, since this "MNVR" precedes an actual translation MNVR.
- H. "Orbit" versus "revolution": These two terms have been used interchangeably and with subtle distinctions since the dawn of the Space Age. We prefer to use "orbit" to refer to the closed path of a space vehicle, as in "orbit adjust burn" or "target orbit." One "revolution" is the act (and time duration) of completing a full circuit in inertial space; it is abbreviated "REV."

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Rendezvous and Proximity Operations Handbook

Appendix: STS Rendezvous and Proximity Operations Experience 1981-1986

Mission Operations Directorate
Flight Design & Dynamics Division

Basic
May 16, 1988



National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

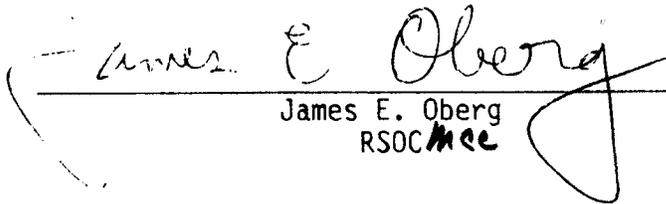
MISSION OPERATIONS DIRECTORATE
RENDEZVOUS AND PROXIMITY OPERATIONS
HANDBOOK

BASIC

APPENDIX: STS Rendezvous and Proximity Operations Experience 1981-1986

May 16, 1988

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Introduction

JSC Publication JSC-10589 (Rendezvous and Proximity Operations Handbook), BASIC (May 15, 1988), describes the standard STS rendezvous and proximity operations procedures and their rationale, including a detailed discussion of Orbiter systems applicable to this mission phase. The handbook is a distillation of analysis and experience. In preparing the book it became clear that a historical narrative of "lessons learned", which also showed how procedures had evolved and matured, would be a useful supplementary reference document. The document rapidly expanded beyond the usual size of a subsidiary appendix and it was decided to publish it separately. This decision had several additional advantages since not all users of the JSC-10589 will need or want the historical background, and since many users may be interested in the background alone. As additional rendezvous experience is accumulated in the future it is expected that addenda to this appendix will be prepared.

ABBREVIATIONS/ACRONYMS

A/G	air to ground
ACQ	acquisition
ACS	attitude control system
ADI	attitude direction indicator
AIF	auto/inhibit/force switch (SPEC 33)
AOS	acquisition of signal
APU	auxiliary power unit
ARCS	aft RCS
ATT DB	attitude deadband
AUTO	automatic
AVG G	average G (acceleration)
AZ	azimuth to target
AZ-DOT (AZ)	azimuth rate
BODY VECT	body vector
BOS	bright object sensor (star tracker)
bp	barber pole (on a talkback)
CB	constant bandwidth
CCTV	closed circuit television
CCW	counterclockwise
CDR	commander (crewmember)
c.g.	center of gravity
c.m.	center of mass
CMD	command
CNCL	cancel
COAS	crewman optical alignment sight
COMM	communication
CR	change request
CRT	cathode ray tube
CSM	command service module
CW	clockwise
C-W	Clohessy-Wiltshire
CUR	current telemetry vector
D	dimension, as in "two-D meter"
DAP	digital autopilot
DB	deadband
deg/s	degrees per second
DH	differential height
D/N	day/night
DELTA-V	delta velocity
DoD	Department of Defense
dps	degrees per second
DPS	data processing system
DR	discrepancy report
ΔH	delta height between target orbit and chaser
ΔV	delta velocity

ΔT	delta time
DTO	detailed test objective
EE	end effector (of RMS)
EL	elevation of target
EL-DOT (EL)	elevation rate
ET	elapsed time (also PET)
EVA	extravehicular activity
EXEC	execute
FD	flight day
PDF	flight data file
FDIR	fault detection, identification, and reconfiguration
FDO	flight dynamics officer
FLTR	filtered (SV)
FOD	Flight Operations Directorate (now MOD)
FOV	field of view
fps	feet per second
FRCS	forward RCS
FSL	Flight Simulation Laboratory
FSW	flight software
ft	feet
ft/s	foot per second
fwd	forward
g	acceleration due to gravity
G&C	guidance and control
GCIL	ground control interface logic
GG	gravity gradient stabilization
GNC	guidance, navigation, and control
GPC	general purpose computer
GPS	general processing subsystem global positioning system
H	orbital height (above surface)
H-BAR	angular momentum vector
HST	Hubble Space Telescope
IAH	inertial attitude hold
I'CONNECT	OMS-to-RCS interconnect
I-load	initial load (software)
IMU	inertial measurement unit
INRTL	inertial
IRT	integrated rendezvous target
ISF	Industrial Space Facility
kft	kilofeet (1000 feet)
KITE	kinetic isolation tether experiment
K-load	constant FSW I-load
LDEF	Long Duration Exposure Facility
LED	light emitting diode

LEO	low Earth orbit
LOS	line of sight
LOSA	line-of-sight angle
LRU	line replaceable unit; i.e., any "black box"
LVLH	local vertical/local horizontal
MC	midcourse correction maneuver
MCC	Mission Control Center (Houston)
MECO	main engine cutoff
MET	mission elapsed time
MM	major mode, software
MMU	Manned Maneuvering Unit
MMU	mass memory unit
MNVR	maneuver
MOD	Mission Operations Directorate (formerly FOD)
MPAD	Mission Planning and Analysis Division
mr	milliradian
MS	mission specialist (crewmember)
mV	stellar magnitude
n. mi.	nautical miles
NAV	navigation
NC	phasing maneuver ("C" for "catch-up")
NCC	corrective combination maneuver
NH	height maneuver
NLOS	normal to line-of-sight
NPC	plane change maneuver
NSR	rendezvous coelliptic maneuver
NSTS	National Space Transportation System (office)
OH	overhead
OI	operational increment (flight software release)
OMS	orbital maneuvering system
OMV	orbital maneuver vehicle
OOP	out of plane
OPS	operational sequence, software
OPS-0	idle mode
ORB	orbital
OTV	orbital transfer vehicle
PAD	preliminary advisory data
PAM	Payload Assist Module
pb	pushbutton
PDP	Plasma Diagnostic Package
PDRS	payload deployment and retrieval system
PET	phase elapsed time
PI	plume impingement
PIR	problem incident report (now called DR)
PL	payload
PLB	payload bay
PLBD	payload bay doors
PLT	pilot (crewmember)

PMG	plasma motor generator
PNL	panel
POCC	Payload Operations Control Center
POP	perpendicular to orbital plane
PRCS	primary RCS
PREL	preliminary
PROX OPS	proximity operations phase
PS	payload specialist
PTC	passive thermal control
R	range to target
R-BAR (R)	radius vector axis
R-DOT (R)	range rate to target, (+) opening, (-) closing
RCS	radar cross section
RCS	reaction control system
RED	radar enhancement device
REL	relative
REL	release (flight software)
REV	revolution about Earth, usually about 90 minutes in LEO
rf	radio frequency
RFPHB	Rendezvous Flight Procedures Handbook
RHC	rotational hand controller
RM	redundancy management
RMS	Remote Manipulator System
RNDZ	rendezvous
ROT	rotation
rpm	revolutions per minute
RPY	roll-pitch-yaw
RR	rendezvous radar
RSS	"root of sum of squares"
sec	seconds
SEDS	small expendable deployment system
SEP	separation
SES	Shuttle Engineering Simulator
SK	stationkeeping
SM	systems management
SMM	Solar Maximum Mission Satellite
SMRM	Solar Max rescue mission (STS 41-C)
SMS	Shuttle mission simulator
SOR	stable orbit rendezvous
SPARTAN	Shuttle Pointed Autonomous Research Tool for Astronomy (a retrievable free-flier)
SPAS	Shuttle pallet satellite
SPEC	specialist display, flight software
SQRT	square root
SR	sunrise
SRM	solid rocket motor
SS	sunset
STDN	Space Station
STRK	Spaceflight Tracking and Data Network
	Star trackers (preferred)

STS	Space Transportation System
SUM	summary
SV	state vector
SYS	system
t	time
tb	talkback
TBD	to be determined
TBS	to be supplied
TDRS	Tracking and Data Relay Satellite
TM	telemetry
TF	terminal phase final
TGT	target
THC	translation hand controller
THETA (θ)	elevation angle of target from Orbiter (local horizontal)
TI	transition initiate maneuver (former acronym for T_i)
T_i	transition initiate maneuver
TIG	time of ignition
TPS	Thermal Protection System
TRK	tracking
TS	target suppress (feature of star tracker)
TSS	tethered satellite system
TSS-D	TSS deployer mechanism
TSS-S	TSS satellite
TVC	thrust vector control
TVR	thrust vector roll
TWT	traveling wave tube (in K-band RR)
UNIV PTG	universal pointing
UP	universal pointing
UPP	user parameter processing (in GPC's)
V	velocity
V-BAR (V)	velocity vector axis
VEL	velocity
VERN	vernier
VGO	velocity to go
VRCS	vernier RCS
VV	velocity vector
X	cross, as in "X-hair"
XLV	X local vertical
Y	Orbiter/target out-of-plane distance (kft)
Y-DOT	Orbiter/target out-of-plane rate (fps)
YLV	Y local vertical
ZLV	Z local vertical

APPENDIX A
STS RENDEZVOUS/PROX OPS EXPERIENCE

Over the course of several years a wide variety of RNDZ and PROX OPS experience has been accumulated. General material has already been incorporated into the body of this handbook, but a mission-specific enumeration of "lessons learned" is presented in this appendix.

RNDZ/PROX OPS missions to date are summarized in table A-I. These include missions for which planning was done, but which were cancelled.

The material in this section has been extracted from flight crew reports, from technical reports, from FDF Rendezvous and Prox Ops books, and from DM43 archives.

TABLE A-1.- STS RENDEZVOUS/PROX OPS MISSIONS

Mission	Launch date	Activities
STS-7	1983 June 18	SPAS-01 PROX OPS
STS-10	1983 Nov.	IRT - mission cancelled
STS 41-B	1984 Feb. 03	IRT practice TRK
STS 41-C	1984 Apr. 06	LDEF deploy; SMM RNDZ (twice)
STS 41-F	1984 Aug.	Spartan - mission cancelled
STS 51-A	1984 Nov. 08	Palapa/Weststar RNDZ /recovery
STS 51-D	1985 Apr.	LDEF retrieve - cancelled
STS 51-DR	1985 Apr. 12	Syncom contingency RNDZ
STS 51-G	1985 June 17	Spartan-1 deploy/retrieve
STS 51-F	1985 July 29	PDP PROX OPS
STS 51-I	1985 Aug. 27	Syncom RNDZ/repair
STS 61-B	1985 Nov. 27	OEX DAP test
STS 51-L	1986 Jan. 28	Spartan Halley (Challenger accident)
STS 61-J	1986	HST rendezvous: cancelled
STS 61-I	1986 Sep	LDEF retrieve: cancelled

- A. STS-7 (STS 31-C) was launched June 18, 1983/1133 GMT, with a crew of Crippen (CDR), Hauck (PLT), Fabian (MS1), Ride (MS2), and Thagard (MS3). STS-7 performed two sessions of PROX OPS with the Shuttle Pallet Satellite (SPAS) to prove out sensors, flight procedures, and plume impingement effects.

The "lessons learned" summary from DA8 relates that

- Radar performance was good (angle rate data noisy).
- RMS operations worked well, variable RMS tip-off rates at release.
- Verified propellant costs for V-BAR and inertial flyaround.
- Plume susceptibility outside quiet zone is dramatic (not LOW Z).

* * * *

The STS-7 experience was summarized by Crippen and Hauck in their conference paper, Orbiter Operations in Close Proximity to Free-Flying Satellites, or Formation Flying in Space. The following excerpts concern procedures:

During PROX OPS, one pilot was actively controlling the Orbiter from the aft station, while the other pilot was seated in the starboard pilot's seat, monitoring Orbiter systems, making any necessary inputs through the computers to the automatic flight control system, and acting as the prompter for the timeline. One of the MS's was at the port aft station to either control the robot arm during payload release and grapple operations, or to control the TV cameras for documentation or ranging (triangulation) purposes. A second MS was seated in the commander's (port) seat, monitoring, via telemetry, the health and commanding changes of the satellite, and of the attitude of the satellite. The third MS floated somewhere in the middle of the other four, taking both motion and still pictures of the operation.

As in any type of flight operation, fuel conservation is critical. A variety of fuel-saving techniques was evaluated during preparations for STS-7. Several are obvious - a few others are not. Since the SPAS satellite was released nonpropulsively from the Orbiter, they were both initially in the same orbit. Energy added to or subtracted from the Orbiter during back-away had to be compensated for later, after the desired stationkeeping position was established, to return the Orbiter to a stable orbit relative to the SPAS. A subsequent rejoin similarly required the expenditure of fuel to initiate the desired motion and a later fuel usage to null that motion when the regrapple position was attained. The lessons are obvious and are direct corollaries of how we manage fuel with aerodynamic machines: Do not use afterburner if military thrust will do. Do not use military if idle will do, and in the no-drag environment on orbit we have the advantage of being able to adhere to the maxim: shut down the engines if you are not using them to move the vehicle.

On STS-7 the orbital altitude of the Shuttle was approximately 160 n. mi. with a resultant 90-minute orbital period. Thus, every hour and a half Challenger passed through a full day/night cycle, with 55 minutes of daylight and 35 minutes of night. MNVR's in close proximity to the SPAS were designed to be accomplished during daylight, constrained such that closure rates were phased and of sufficient magnitude to complete regrapple in daylight. Obviously, to conserve RCS propellant, it was desirable to make the smallest Orbiter velocity changes possible, compatible with lighting constraints and other test objectives.

In addition to this "slow is good" rule, there is another, which is not quite so obvious: Do not put energy into out-of-plane MNVR's. As stated earlier, since SPAS was released from the Orbiter nonpropulsively, in an ideal environment with no other perturbations, their orbit planes should have remained coincident. Any (small amount of) energy added to either spacecraft perpendicular to the orbit plane resulted in a very small tilting of the affected orbit plane, but the resulting relative motion was periodic. Thus, as long as the out-of-plane motion or misalignment did not overly complicate the formation flying problem, no propellant was used to null it. In general, 10° of azimuth sighting deviation (with the COAS) was used as the boundary for making out-of-plane corrections.

Finally, a few words on the use of automatic versus manual control modes are in order. As was mentioned previously, there are several AUTO Orbiter rotation modes which are available. Early in flight-techniques development it was determined that whenever both translational and rotational MNVR's were required simultaneously, it was much easier (and more efficient) to let the AUTO mode perform the ROT while the translation was done manually. Thus, attitude MNVR's were designed to take advantage of the AUTO rotational capability inherent in the DAP.

PROXIMITY OPERATIONS

Phase One

The initial portion of the PROX OPS involved the following: releasing the SPAS above the Orbiter in an Earth-oriented sense. A translation of the Orbiter was then initiated away from the SPAS along the Earth R-BAR. At 200 feet below the SPAS, the orbital mechanics effects were allowed to let the Orbiter proceed in front of the SPAS while the pilot manually rotated the Orbiter about its Y axis to maintain the SPAS in the COAS (fig. A-1). At a range of 1000 feet, the opening rate was nulled, the Orbiter placed in inertial attitude hold, and a +X translation was initiated to move the Orbiter upward toward the SPAS V-BAR. Upon arrival at the V-BAR, the Orbiter was placed in a tail-down, local-vertical flying mode and all relative rates were nulled. Stationkeeping at the 1000-foot point on the V-BAR was maintained a little over 2 hours. A 1-foot-per-second translation was then initiated toward the SPAS. Appropriate braking gates were used on the approach.

Relative rates were nulled with the SPAS in the field of view of the robot arm RMS wrist camera. The SPAS was then successfully grappled with the RMS.

The initial release on the R-BAR by the RMS was very stable, as were all releases. At the time of the release, the Orbiter was in a free-attitude control mode (MAN PULSE) and the SPAS was over the payload bay. Visibility at this point was excellent. After the stability of the SPAS was noted, VERN attitude control in a bottom-down, nose-forward, local-vertical mode was selected for the Orbiter. Rotation of the SPAS about each of its axes was commanded and checked. During this check, a very slight opening rate on the SPAS was noted.

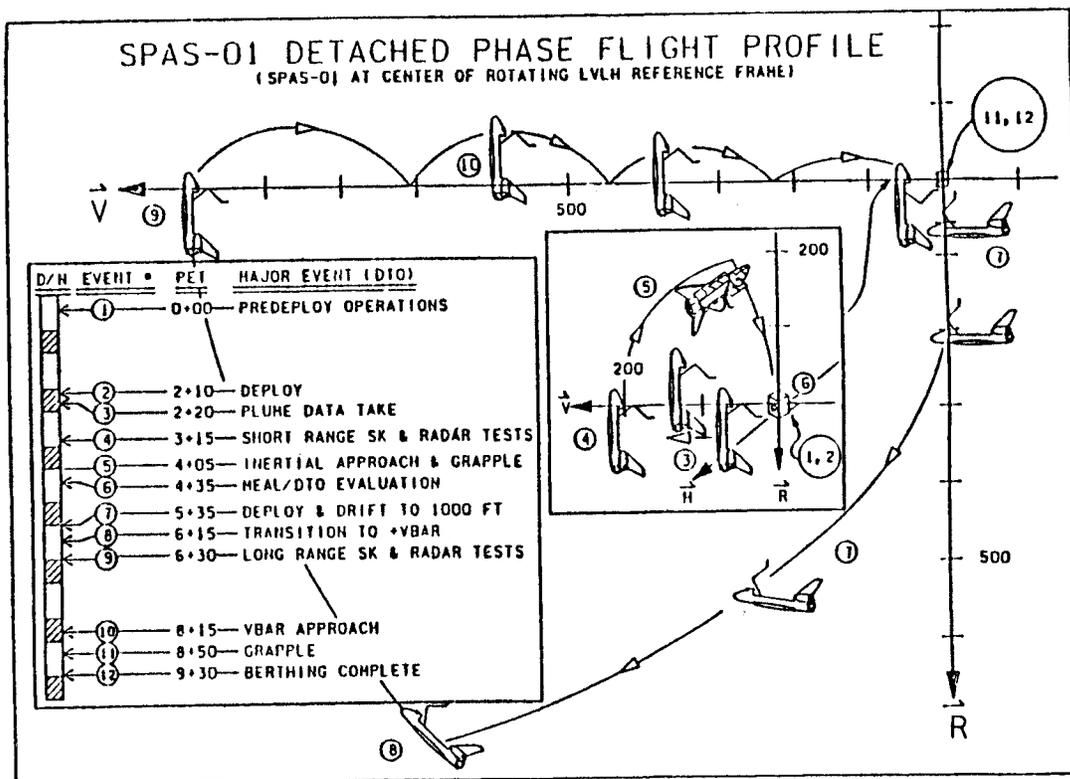


Figure. A-1.- SPAS profile-1.

After the check was complete, NORM jets in the low Z mode were used to initiate an opening rate of approximately 0.25 ft/s. As was previously stated, the low Z mode fires + and - X thrusters for +Z translation to minimize plume impingement on the free-flying satellite. Pulse size for the initial translation was 0.05 ft/s. Then a pulse size of 0.01 ft/s was selected for fine control. This was accomplished by switching between DAP's A and B. Thereafter, control was manually switched back and forth between these two pulse sizes as the control task demanded. Control inputs were also initiated to move the Orbiter aft, such that SPAS moved forward toward the COAS.

At approximately 70 feet, search was initiated on the radar and it locked on shortly thereafter. Both range and range rate were very stable and remained that way. The line-of-sight rates were observed to be intermittently stable and oscillatory with an occasional OFF flag. At an indicated range of 200 feet, ROT about the Orbiter X and Z axes were placed in inertial attitude hold and the Y axis in a free mode. Vernier jets were also selected.

The 200-foot point was reached at approximately the same time the SPAS had reached the field of view of the COAS. At this point the RHC was used in a PULSE mode (pulse size 0.01 deg/s) to maintain SPAS in the COAS in the pitch axis only. Roll and yaw were placed in inertial attitude hold (MAN DISC RATE). Translational inputs were terminated, and the orbital effect of being in a lower orbit was allowed to cause the Orbiter to accelerate ahead of the SPAS. No attempt to correct out-of-plane motion was made throughout phase one until the final approach. The SPAS was placed in inertial at this point with minor attitude corrections to optimize pointing for photography and television.

At a range of 1000 feet, the Orbiter was placed in inertial attitude hold and the opening rate, which was approximately 1.3 ft/s as indicated by the radar, was nulled. Since these firings were primarily retrograde, they would tend to make the Orbiter fall to an even lower altitude. However, motion of the SPAS in the COAS was used as the cue for initiating the +X translations necessary to maintain the SPAS in the center of the COAS. This initiated the transition toward the V-BAR. During this transition, the radar range rate readout was used to null opening and closing rates. Upon reaching the V-BAR as indicated by the ADI and UNIV PTG display, the Orbiter was placed in a tail-down, bottom-forward, local-vertical flying mode. Again, using the motion of the SPAS in the COAS, the upward motion of the Orbiter, with respect to the SPAS, was nulled with -X translational inputs. The SPAS was placed approximately 2.5° low in the COAS to account for placing the Orbiter center of gravity on the velocity vector of the SPAS. Radar range rate was again nulled.

Long-range stationkeeping was initiated by opening up the normal jet ATT DB from 2° to 5°. This was to minimize the possibility of attitude control NORM jet firings when a translational input was made. Vernier jets with a 0.5° DB was the mode normally selected while stationkeeping. Momentary selection of normal jets was made when a translational input was required. With the availability of radar range and range rate, this was a very easy task. There were periods of up to half an hour without the requirement for crew inputs.

Two radar tests were performed at the 1000-foot point. Each involved maneuvering the Orbiter 20° out of attitude--one was a -Y (yaw) rotation and the other a +X (roll) rotation. Twenty degrees is on the edge of the radar search envelope. The radar lock was broken once the Orbiter was in attitude and the radar antenna was manually driven to zero in

elevation and azimuth. Search was initiated while holding the offset attitude for the -Y rotation and after initiating the maneuver back to normal local vertical for the -X case. In both cases the radar achieved a lock-on in short order.

Night viewing was also evaluated at the 1000-foot point. Having the SPAS running lights on was the only satisfactory lighting configuration. The PLB bay lights had no effect on SPAS visibility. This was also true of the RMS end-effector light. A color television camera proved to be useless with the SPAS running lights turned off. The black and white camera was not evaluated because a cable-wrap problem prevented it from being properly positioned. While the SPAS was visible in the improved crew optical sight (ICOS) with the running lights on, the SPAS was barely discernible when they were turned off. ICOS night-SPAS visibility without running lights was so poor it would not have been detectable without prior knowledge of its position. The ICOS was not a satisfactory stand-alone night viewing aid. It should also be noted that this evaluation was made with a full moon, and that the first point that the SPAS was visible without running lights was approximately 300 feet. Also, it is important to note that stationkeeping at 1000 feet would not have been possible at night without the visibility provided by the running lights. Some means of illuminating satellites is mandatory when stationkeeping or making final approaches at night.

The final approach was initiated at night at a time designed to reach 200 feet at sunrise. This timing worked out very well. The normal jet DB was shrunk from 5° to 2°. A closing rate of 1 ft/s was initiated using the radar range rate. Orbital mechanics then dictates periodic up (+X) firings to keep the Orbiter on the V-BAR. Again, vernier jets were used except when a translational command was required. The braking technique used was at 500 feet to slow to 0.5 ft/s, at 400 feet to 0.4 ft/s, at 300 feet to 0.3 ft/s, and at 200 feet to 0.2 ft/s. From 200 feet until final stop, less than 0.2 ft/s closure rate was maintained. After slowing to 0.2 ft/s at 200 feet, low Z was selected for the remainder of the approach. Plus X translational inputs were made to move the SPAS aft where the RMS was positioned over the PLB. This position was the same as used for the release. Radar lock was lost at approximately 70 feet. The B television camera view showing both the RMS and SPAS was used to judge closure rate. The RMS and effector camera, which was pointing parallel to the Orbiter +Y axis, was used to null rates before turning the task over to the RMS operator. The Orbiter and the SPAS were placed in free drift prior to RMS grapple.

Phase Two

The afternoon (phase two) PROX OPS had two main objectives. First, to define the pressure field of a single (RCS) jet plume (fig. A-2). Second, to demonstrate the capability to MNVR the Orbiter to an inertial position out of the orbital plane of the satellite, and close to capture range from that position.

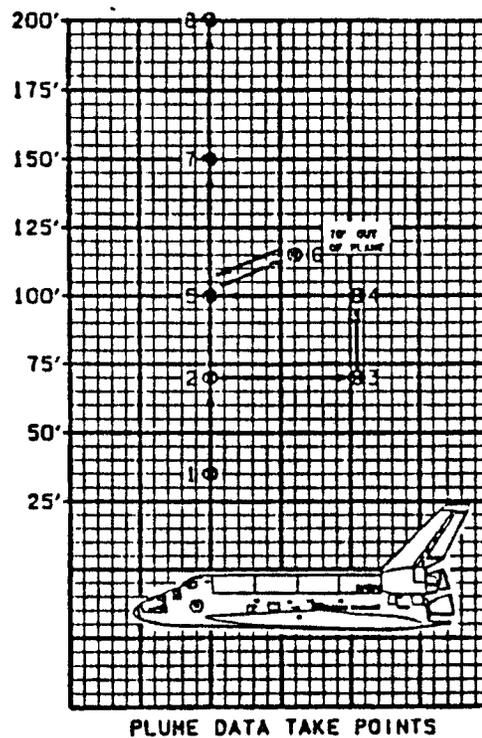


Figure A-2.- Plume data take points.

Satisfaction of both of these objectives was key to RNDZ with a crippled satellite (Solar Maximum) on Mission 13 with the intent of repairing it on orbit.

Due to a thermal problem with the SPAS avionics, the initiation of phase two was delayed for one orbit, permitting cooling of the avionics while the SPAS was parked on the end of the RMS in a benign attitude. To broaden the experience and evaluation base of PROX OPS, the two pilots swapped positions, as did two MS's.

To review, the Orbiter was now in the tail-to-Earth (-XLV) attitude with the belly in the direction of the velocity vector. The MS, using the arm, positioned the SPAS over, and 35 feet from, the overhead windows and then released it. The SPAS position was stable and the pilot used the THC to back away very slowly (0.2 ft/s) from the SPAS. The Orbiter ROT DAP was in the Earth pointing (LVLH) mode, which automatically kept the proper Orbiter orientation within the selected DB's. The DAP's were configured to provide .03 ft/s translation pulses when maneuvering between data points (DAP A), and to provide various pulse sizes (0.065 to 1 s pulse duration) when firing the forward up-firing thruster at SPAS during the data takes (DAP B). The pilot made small translational corrections to maintain the SPAS centered in the optical sight.

When Orbiter-to-SPAS separation had increased to 50 feet, as determined by using TV tilt angles for triangulation, the Orbiter attitude hold mode was inhibited and a single up-firing thruster was fired for 0.065 s. Recorders onboard the SPAS monitored translational accelerations and rotation rates. After 10 s of Orbiter free drift, during which a mild, nose-down ROT rate ensued, the AUTO LVLH DAP mode was reengaged and the autopilot returned the Orbiter to the specified tail-down attitude. This first data point was done without nulling opening rate. No SPAS attitude reaction was noted during this data take or any other. The only visual confirmation of plume impingement was a ruffling of some of the SPAS thermal blanket material.

The separation was continued to the 70-foot data point (number 2) where opening rate was nulled. After data point 2, an Orbiter forward translation was initiated to position SPAS over the aft TV's. During this translation an attempt was made to lock on the RR, but the initial attempt at about 80 feet was unsuccessful. At both aft data points (3 and 4) there was no SPAS motion detected immediately after firing the forward RCS jet. But when AUTO DAP was reselected in both cases, the resultant aft RCS jet firings caused SPAS rotations and translations that were easily apparent.

After data point 4 was taken, the subsequent AUTO DAP selection and subsequent aft jet firings resulted in a 1.94 deg/s rotation of SPAS as monitored on the CRT telemetry. While SPAS was aft, it became apparent that the TV tilt-angle data was giving erroneous range information. Another attempt was made to lock on the RR, and this was successful (slant range ~120 feet). From radar data, it was apparent that the aft RCS plume impingement had caused SPAS translation away from Challenger. The RCS fuel budget was in good shape, and there was no hesitation to reclose to 100 feet as the Orbiter was translated aft to place SPAS over the COAS in preparation for data point 5.

After taking this data point, even greater care was taken to stabilize the Orbiter/SPAS relative position in preparation for the simulated out-of-plane data point, in order to minimize relative transition during this period when visual position monitoring was not as precise. The universal pointing display was used to input a 30° roll angle and the Orbiter was rotated at 0.5 deg/s to the test position. After this test point and the subsequent Orbiter rotation back to -X LVLH attitude, it was noticed that there was about a 10- to 20-foot relative drift (SPAS aft). This was easily corrected and the remaining 150 feet and 200 feet data points were taken. During all of the data points, care was taken to observe the preflight agreed-upon positioning limits of +10° from reticle center while taking points 1, 2, 5, 7, and 8.

Jet pulse durations for the test had been sized to produce SPAS ROT's of ~0.15 deg/s. Preliminary data from SPAS indicated that the jet plume characteristics had been well modeled prior to the flight. This gave NASA engineers increased confidence that the jet plume sphere of influence would be well understood in sufficient time to incorporate

even more accurate models in simulations that led up to the S M repair mission.

The plume data take was completed prior to the next sunset and the DAP was configured for the 200-foot stationkeeping tasks. Translation pulse sizes of 0.05 and 0.01 ft/s were available in DAP's A and B, respectively, with both DAP's loaded with attitude DB's of 2.0° and 0.5° for NORM and VERN jets, respectively. Low Z mode was not used for stationkeeping. The stationkeeping task was easily accomplished with range (R) and range rate (R-DOT) from the RR provided on the digital displays. Elevation and azimuth were generally monitored visually through the COAS. Stationkeeping was easily accomplished during the 45 minutes allotted, with relatively few Orbiter inputs required. Generally, DAP B was selected to make use of the small (0.01 ft/s) pulse size. Cycling between NORM and VERN jets permitted use of the small VERN attitude DB to resolve visual position ambiguities between Orbiter attitude and translation (X or Y axis) offsets.

SPAS was commanded to a computed inertial attitude in preparation for the inertial 200-foot fly-around and inertial approach. When properly oriented, the Orbiter MNVR option attitude that would coalign the Orbiter and SPAS axes was entered in the UNIV PTG display. START MNVR was executed, low Z was selected, and the Orbiter rotation rate of 0.15 deg/s was initiated. The pilot made translation commands to maintain SPAS in the COAS and the 120° out-of-plane fly-over was initiated. Initial translation inputs were made using 0.05-ft/s pulses and were easily controlled. At no time did it seem that a response lagged demand, and it is felt a higher ROT rate than 0.15 deg/s would have been possible. Once the translation was initiated, very few inputs were required at all. Range was stable at 200 feet for at least the first 90° of rotation. This suggests that either orbital mechanics effects were negligible, or these effects were compensated by DAP characteristics. After approximately 90° of Orbiter ROT, a closing rate was induced (not intentional), which suggests some DAP or orbital mechanics interaction. As an approach to SPAS was the ultimate goal, +Z inputs were made to keep closing rate less than 0.2 ft/s, but no effort was made to null the rate.

When Challenger had reached the final desired attitude, THC inputs were made to maintain SPAS in the COAS, and thus stop Orbiter translation. This was easily accomplished. Challenger was maintained in inertial attitude hold and desired deceleration braking gates were observed.

Final approach was done with SPAS centered in the COAS. By monitoring SPAS/Orbiter range and range rate by apparent position on the TV monitors (radar lock was lost at 60 feet on the digital display), closing rate was nulled as the SPAS appeared on the RMS wrist camera field of view. Orbiter Y translation was monitored out-the-window, whereas Orbiter translation was monitored both out-the-window and on the arm wrist camera (the EE CCTV) monitor. Orbiter inputs were terminated and command of the arm was turned over to the mission specialist with a

small SPAS-forward translation in progress. The grapple was completed without incident.

SUMMARY

The entire day of PROX OPS went extremely well. This was primarily due to the detailed procedural work conducted preflight, excellent handling by the ground of a SPAS thermal problem, and outstanding flight characteristics of both the Orbiter and the SPAS.

In short, the Orbiter proved to be a very responsive vehicle that was straightforward to fly in the vicinity of another satellite, given the proper experience base with ground simulations. Fuel usage corresponded very well with that predicted preflight. The radar worked well at the ranges tested, slightly greater than 1000 feet. The only Orbiter deficiency noted was the lack of capability to light the TGT at ranges greater than 300 feet, which will be required for nighttime station-keeping on non-illuminated TGT's.

* * * *

A report, Ku-Band - The First Year of Operation by J. W. Griffin et al, described one problem on STS-7. "The inertial line-of-sight rate data was not useful to the crew due to large excursions. Although these excursions were predicted before the mission, they represented an out-of-spec condition. Later analysis found that the original analysis had neglected the effects of finite null depth in the monopulse pattern. A finite null depth represents a significant gain reduction at boresight when compared to an assumption of infinite depth. The error caused a low servo gain and the resultant poor rate performance."

- B. STS 41-B (STS-11) was launched February 3, 1984/1300 GMT, with a crew of Brand (CDR), Gibson (PLT), McNair (MS1), Stewart (MS2 and EVA2), and McCandless (MS3 and EVA1). One detailed test objective (DTO) involved PROX OPS with an ejected tracking balloon, the integrated RNDZ target (IRT). Planned MNVR's are shown on figure A-4. Due to structural failure in the IRT launch canister, the protective-staves jettison pyro was never initiated following deploy, and the initiation of balloon inflation, while still constrained by metal staves, led to overpressure disintegration of the IRT. An abbreviated set of tests was still conducted.

(Note: After months of negotiating, an IRT had also been manifested on DOD STS-10 mission, but major delay of that mission led to loss of that flight opportunity. See figure A-3.)

The DAB "lessons learned" reported that

- STRK and radar sensors worked better than specification (no RNDZ due to balloon system debris following explosion).
- MMU running lights were essential to track the MMU in darkness.

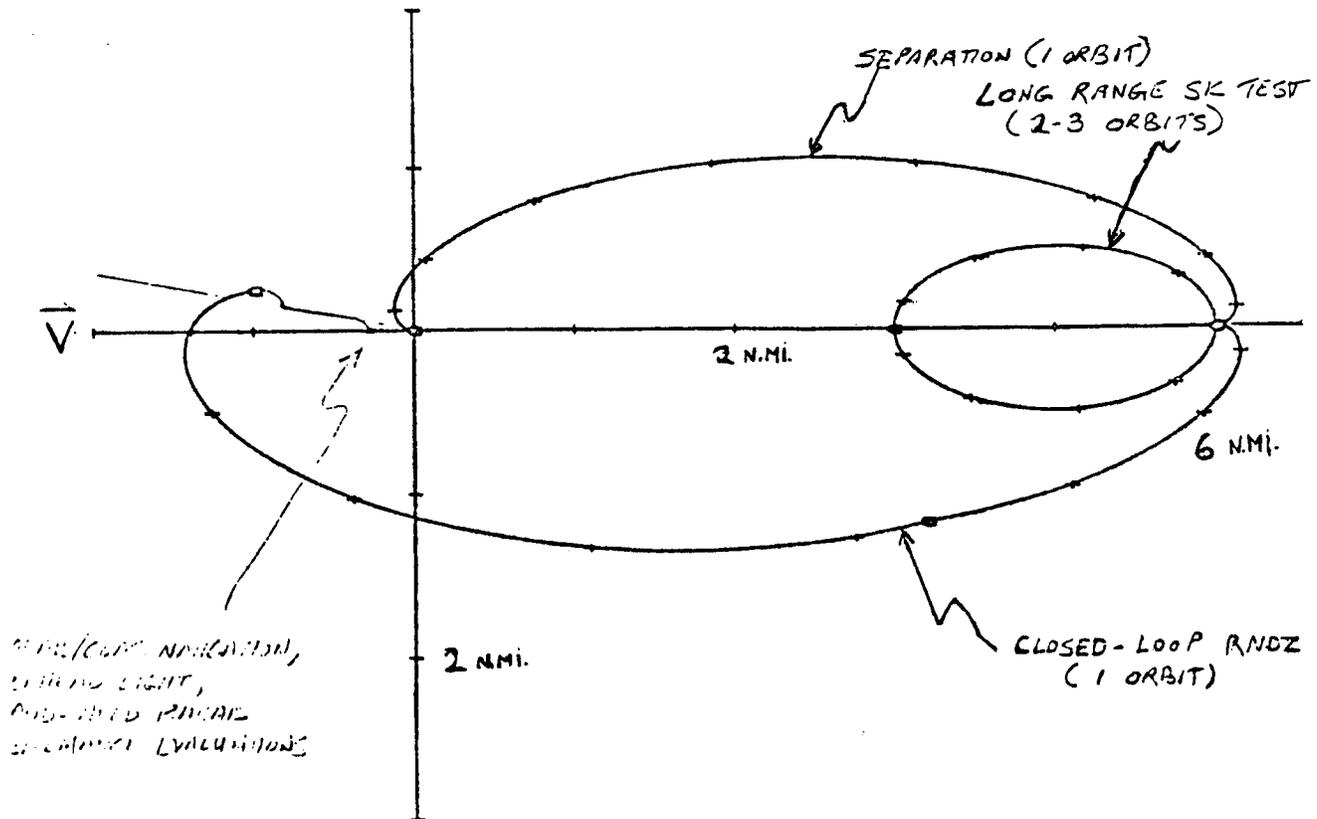


Figure A-3.- STS-10 planned profile (not flown).

- Laser ranging was marginal, range rate was too noisy to use (laser system pointing was tedious and required full time attention from one crewman).
- MMU rescue technique was developed preflight and conceptually verified during retrieval of foot restraint.
- MMU rescue plan developed as Orbiter active (vs. other MMU) to minimize number of active vehicles, plus Orbiter performance "well known."
- Breakout MNVR executed in response to balloon system explosion, to assure Orbiter/TGT balloon did not come into contact.

RENDEZVOUS PROFILE - PHASE 1
 (IRT AT CENTER OF ROTATING LVLH REFERENCE FRAME)

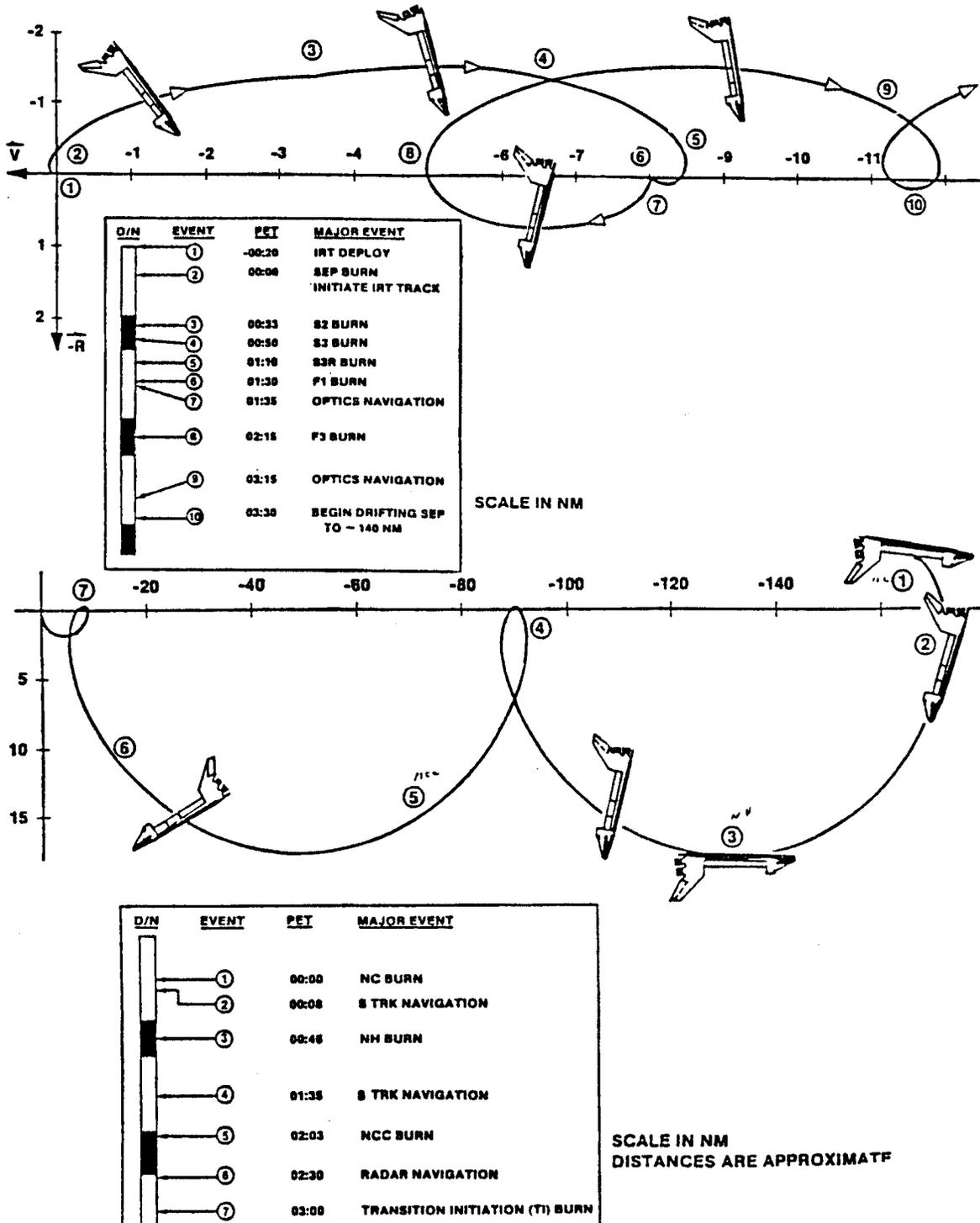


Figure A-4.- STS-11 Rendezvous profile (IRT at center of rotating reference frame).

- C. STS 41-C (STS-13) was launched April 6, 1984/1358 GMT, with a crew of Crippen (CDR), Scobee (PLT), Hart (MS1), Van Hoften (MS2), and Nelson (MS3). The crew deployed the LDEF satellite, and then performed two RNDZ's with the disabled Solar Maximum satellite, capturing and repairing it on the second attempt. This was the first Shuttle Orbiter RNDZ. The planned and actual SMM RNDZ profiles are shown in figures A-5 and A-6.

The DAB "lessons learned" list included

- Spacecraft (SMM) was highly visible and was picked up in STRK early in RNDZ (~200 n. mi.).
- STRK passes were occasionally very noisy due to small differences in inertial measurement-unit midvalue-select routine in GPC software.
- Forward RCS fuel savings techniques were developed for second RNDZ attempt (MNVR to attitude using tail-only PRCS, delete multiaxis burns where possible, hold attitude on VRCS).
- Breakout MNVR strategy developed for all points along RNDZ and PROX OPS trajectory to assure unplanned contact does not occur. Breakout implemented at end of first capture attempt.
- Orbiter separation from spacecraft after first RNDZ occurred faster than planned. Problem had previously been suspected/observed and is still under analysis. Suspect orbital energy growth due to Orbiter plume impingement/scarfing during attitude control pulses with VRCS.
- Orbiter plume effects can be significant (surface area and orientation dependent) even when spacecraft is in quiet zone.
- Orbiter translations and ROT's using low Z mode use up to 12 times amount of ideal propellant; low Z only effective for single Z axis braking and must be used judiciously.
- Orbiter active MMU rescue analyzed preflight and found to be very costly for three bodies (avoid collision, keep view of satellite) resulting in relatively high propellant budget to allow MMU free flight (about three times alone).

- C. STS 41-C (STS-13) was launched April 6, 1984/1358 GMT, with a crew of Crippen (CDR), Scobee (PLT), Hart (MS1), Van Hoften (MS2), and Nelson (MS3). The crew deployed the LDEF satellite, and then performed two RNDZ's with the disabled Solar Maximum satellite, capturing and repairing it on the second attempt. This was the first Shuttle Orbiter RNDZ. The planned and actual SMM RNDZ profiles are shown in figures A-5 and A-6.

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- Forward RCS fuel savings techniques were developed for second RNDZ attempt (MNVR to attitude using tail-only PRCS, delete multiaxis burns where possible, hold attitude on VRCS).
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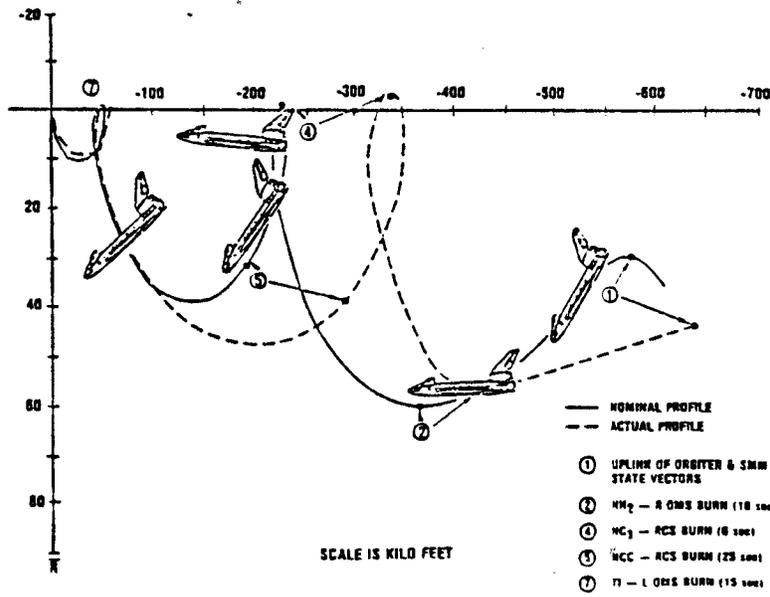


Figure A-5.- SMRM rendezvous.

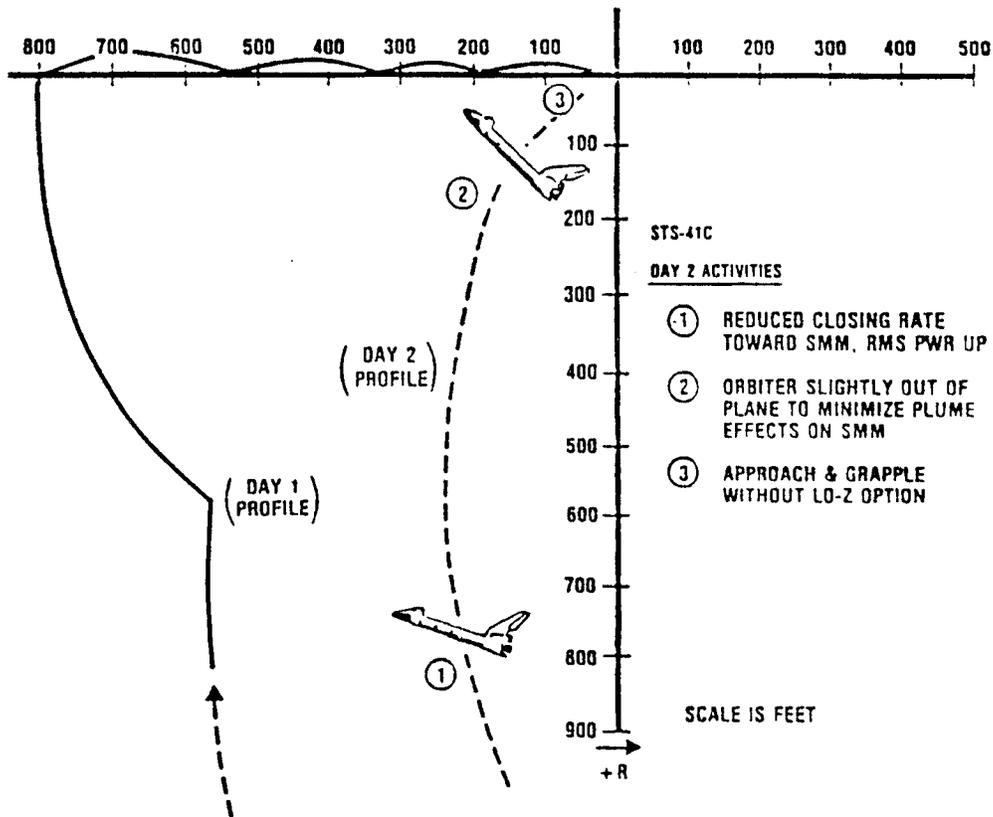


Figure A-6.- SMRM final approach 1 and 2.

The 41-C flightcrew report made these comments on RNDZ operations.

LDEF

The release and separation of LDEF were nominal in all respects. The end effector mode was entered, and the Orbiter was placed in free drift about 2 minutes before the release. The first few inches of RMS motion after the release were done with vernier rates and a minimum THC input. During the 3 minutes following the release, no relative motion was observed using the trunnion pin overlay on the CCTV monitor. The 0.5 ft/s postgrade separation rate was verified by radar at about 100 feet, and the laser range finders tracked to about 200 feet.

The REL NAV function was used with the radar as its input. At about 300 feet, several radar angle marks were rejected with a residual of about 4°. It seemed that the likely cause at this close range was a shift of the tracking from one point of the LDEF to another as the aspect angle changed. At about 1200 feet the Ku mode was changed to GPC. The radar broke track momentarily and then reacquired with angle residual of about 7°. The bad angles were rejected until AUTO track was reestablished at about 1800 feet. The bad angle data appeared to have been caused by a sidelobe tracking the TGT. Radar TRK was discontinued at 2800 feet. At 25,000 feet, radar acquisition in GPC was attempted with the Orbiter in -ZLV, nose forward. TGT track was immediate and the REL NAV performed nominally until the radar track was discontinued at about 35,000 feet.

RENDEZVOUS

The onboard-RNDZ phase began on day 3, 1 hour before the NH burn, and ended at the V-BAR stationkeeping with the initiation of proximity operations. A second RNDZ on day 5 was completed using similar procedures without the need for an NH burn. In order to conserve propellant on day 5, all of the attitude maneuvers were done in vernier reaction control system (VRCS) at 0.2 deg/s, instead of the nominal 0.5 on PRCS.

The first STRK pass began at about orbital noon, three REV's before the rendezvous. The -Z STRK initially began tracking a star that was several degrees from the predicted LOS to the TGT. A BREAK TRACK was commanded and the TGT was acquired on the next attempt. The initial residuals were small, but were randomly changing by more than the 0.05° limit per NAV cycle. AUTO editing was selected since the residuals seemed to be centered on the TGT. The FILTER MINUS PROP (F-P) parameter varied between 1 and 4 kft in response to the noisy data, and the STRK pass ended with 173 marks and an F-P of 1 kft. The TGT was barely visible 10 minutes after orbital noon and could be marked with the COAS at 20 minutes. The range residual was approximately 600 kft.

The second STRK pass occurred at about 250 kft and had similarly noisy data at times. It ended with 152 marks and an F-P of 5 kft. By contrast, the -Z STRK showed no noise during either pass of the day 5

RNDZ. With 155 marks on the first pass and 101 on the second, the day 5 F-P's were 2 kft and 1 kft. The only day-5 STRK anomaly occurred when a piece of ice, visible in the COAS, caused the STRK to temporarily break track with the TGT. The angles were rejected for two NAV cycles, and the TGT was automatically reacquired.

The radar failed self-test with a "333.3" signature as it had several times earlier in the mission. The MCC reported that the failure was caused by unexplained noise and that there was no degradation in the radar. One curiosity was noticed on the REL NAV display at the conclusion of the self-test. REL NAV has interpreted the self-test as data and computed the residuals based on a range and range rate of "333.3". This phenomenon had not been observed in any simulation and care was taken not to allow the data into the filter.

On each RNDZ the radar initially began tracking at about 114 kft, broke track, and reacquired at about 104 kft. The initial range residual was 1.8 kft on day 3, and 0.5 kft on day 5. The radar track was solid in range, range rate, and angles. At the suggestion of the MCC, radar angles were selected instead of the third STRK pass on both day 3 and day 5.

Throughout training, and during each RNDZ, the downrange position of the transition initiate MNVR was observed to increase from the nominal -48 kft target to as far as -58 kft on day 3. The resulting trajectory on day 3 was greater than 3-sigma long. Typically, the NCC burn would be trimmed to within 0.2 ft/s in each axis, and a preliminary targeting of Ti would confirm that the burn had hit the -48 kft TGT within 1 kft. As the intermediate and final solutions were computed with little or no radar updates to NAV, the trajectory would gradually become longer. The day-5 trajectory was at -52 kft, between 1- and 2-sigma long. This phenomenon of the range to the TGT increasing as compared to the predicted range, seemed to continue after Ti. The first two midcourse burns on both day 3 and day 5 were 1 to 2 ft/s radially toward the Earth, indicating that the range to the TGT was greater than the range predicted immediately after the preceding burn. In each case, the TIG slip of the elevation burn MC2 was near, or slightly beyond, the 5-minute limit.

The final two midcourse burns were small on both day 3 and day 5, and the trajectory was nominal from sunrise through the manual trajectory control phase. No pointing errors were evident at sunrise, and an inertial attitude was established at the nominal time of MC2 + 22:00. Very few THC inputs were required to maintain the inertial line of sight. At 2000 feet, the range rate was about 7.5 ft/s, and the initial braking was done to reduce it to 4 ft/s. At 1500 feet, some additional braking was required to meet the 2 ft/s gate. On day 3, the closure was stopped at 800 feet, and the V-BAR was established before orbital noon. On day 5, the closure rate was maintained to conserve FRCS propellant. This resulted in reaching the V-BAR at 350 feet. This type of approach is recommended for future RNDZ.

The backup techniques for determining range and range rate during the manual trajectory-control phase required the use of overlays on a CCTV monitor. This technique would not have been usable because of the inability of the CCTV ALC loop to regulate on a small brightly-lighted target against a black background. Manual control of the iris may have helped, if time had permitted. Ranging by measuring the subtended angle of the TGT in the COAS is probably adequate for trajectories that are not badly dispersed.

PROXIMITY OPERATIONS

On the initial approach to the Solar Maximum satellite, the Orbiter was slowed to 0.2 ft/s at 250 feet. Low Z was selected at 200 feet. Final braking was initiated with the intent of parking the Orbiter between 150 and 200 feet on the V-BAR, and stationkeeping during the orbit night phase. At this time, the Solar Maximum satellite was approximately 2° high in the COAS. The closure rate could be eliminated, but within a very short time the attitude corrections, which were automatically responding to DB excursions, would reinitiate a closure rate of 0.2 ft/s.

Attitude control was maintained with NORM jets during this period, because VERN jets had demonstrated a similar closure problem in simulations. Preflight simulation had also randomly demonstrated this closure problem with low Z NORM jets, but not to the degree experienced during flight.

Range continued to decrease, and extreme jet braking activity proved ineffective in stopping the closure rate. Finally, at 80 feet, the Solar Maximum satellite was moved to 8° high in the COAS to try to use the orbital mechanics effect of having the Orbiter c.g. well below the Solar Maximum satellite to produce an opening rate. This worked with some degree of success, and the Orbiter was backed out of 140 feet. However, the closure rate started again at the very slow rate. As a result of this exercise, the low Z control mode was not considered a viable stationkeeping mode.

With the Orbiter lighting configuration, 250 feet was considered the maximum stationkeeping distance during orbital night. For some payloads, 250 feet may be too close for NORM jet activity without low Z. If a requirement exists to station keep during night periods outside of 250 feet, better Orbiter exterior lighting should be provided, or stationkeeping may not be a viable option. It should also be pointed out that lighting was adequate for a comfortable approach and grapple during the orbital night period as long as the range was less than 250 feet at sunset.

Trajectories with low beta angles, where the path of the Sun comes very close to the TGT, which was the case for the Solar Maximum satellite, were a difficult visual situation. It was important during stationkeeping to be in as stable a situation as possible because it was extremely painful to try to observe the TGT with the Sun in the crews'

eyes. The radar range and range rate helped for the opening/closing rates, but the LOS meter was too noisy to be useful, hence there was no reasonable way to make up for the loss of visual tracking for up/down and left/right motion.

For the RNDZ, the final approach was made with no intent to station keep. The Orbiter was again slowed to 0.2 ft/s at 250 feet on the V-BAR and low Z was selected at 200 feet. To avoid the Sun interference problem, inertial attitude hold was selected about 15° earlier than the "end-on" approach that had been practiced in simulations for rotating grapples. This totally eliminated the Sun problem and proved not to hamper the grapple operations.

To ensure proper braking, low Z was deselected at approximately 80 feet with the Solar Maximum satellite over the PLB where plume impingement did not appear to be a problem. A small amount of rippling of the Mylar on the satellite was noted, but no attitude changes were observed due to jet firings. The Solar Maximum satellite translation was stopped when it was in the RMS wrist camera field of view for the grapple attempt.

Parking the satellite over the bay for the RMS attempts with a satellite of this size while rotating, even tumbling as it was on the first attempt, was not considered a problem.

* * * *

A detailed account of Ku-band RR performance on STS 41-C was given in Ku-Band - The First Year of Operation, by J. W. Griffin et al. The relevant section says:

Operations for the Ku-band on STS 41-C began 1 hour and 40 minutes after launch with deployment and an initial self test. With the self-test having indicated no problems and no evidence of extraneous TGT's, the system switched to communications mode until just prior to deployment of the long duration exposure facility (LDEF) 25 hours later. Immediately upon switching into radar mode, received signal strength spikes, and false TGT indications (identical to those seen on STS-11) were observed. As a result, two subsequent self-tests failed. Suddenly, 15 minutes prior to the release of LDEF, the indications stopped. Shortly after the release, the radar track signal went high and displays reported 88 feet. As Challenger backed away at 2.0 ft/s, the radar remained in track until 2500 feet when the system was returned to communications mode. An hour and a half later the system was switched back to radar. During a successful self-test, one RSS spike was observed. Minutes later after reconfiguration, the radar achieved reacquisition of LDEF on the first attempt at 25,276 feet, with an opening velocity of 4.5 ft/s. Track continued in excess of 35,000 feet, at which time the system was again returned to communications operations, where it remained for over 6 hours. Immediately upon switching to radar, the false TGT indications returned and two subsequent self-tests failed. Following yet another switch to communications mode, the radar was readied for the Solar Maximum satellite acquisition with the Kalman filter propagating the relative states.

Acquisition of the Solar Maximum occurred at 101,553 feet. Based upon an estimated RCS of 2.0 square meters, acquisition was expected at 85,000 feet. RSS data throughout the subsequent track to 89 feet showed the Solar Maximum satellite tumbling at 1/6 revolution per minute. Stationkeeping at 100 feet, mission specialist Dr. George Nelson translated the separation distance aboard his MMU and valiantly attempted harnessing the tumbling satellite. Unsuccessful in his attempts, Nelson returned to the Orbiter, and Challenger was backed away overnight.

During the separation, with the Solar Maximum satellite inside the minimum acquisition and distance of 100 feet, the radar was commanded to reacquire. Confusion in the relative position of Challenger and the Solar Maximum satellite, created by the Orbiter's maneuvering to the retrograde burn attitude, caused the initial manual and autotrack acquisition attempts to fail. Within seconds upon switching to GPC acquisition, the radar found the Solar Maximum satellite at 5298 feet, and continued to track to 54,000 feet when the system was reverted to communication mode.

With one exception, the second Solar Maximum RNDZ was almost a duplicate of the first, displaced by 48 hours, with acquisition at 110,000 feet and break track at 88 feet. At 54,555 feet, the radar reported an ambiguous velocity of 114 ft/s instead of the correct velocity of 8 ft/s. Subsequent data analysis showed the anomalous reading to be a result of a TGT fade. A reasonability check of the Kalman filter correctly rejected the mark. Mission specialist Terry Hart successfully grappled the Solar Maximum satellite with the RMS almost exactly 4 days into the mission. Two minutes later, Ku-band returned to COMM to provide the world with television coverage of the initial inspection within the payload bay.

On flight day 6, after the Solar Maximum satellite repair and yet another failed self-test, the radar was able to acquire the satellite at 198 feet as Challenger backed away, in spite of many false TGT indications. Track was maintained to 680 feet where the antenna reached a position that indicated it was about to illuminate the payload, which turns off the transmitter. Following some spikes on the RF power monitor and an unsuccessful attempt to reacquire because the antenna was pointed away from the TGT, the system returned to communications until flight day 7. Believing the apparent interference to be aboard the Orbiter, an attempt was made to locate a source on flight day 7. During the test, four self-tests were performed with three failing in the presence of false TGT's. Also during the test, the S-band communications system was reconfigured along with switching several elements that input to both S-band and Ku-band. In all configurations the false signals were present. After the mission, similar interference tests were conducted at the Orbiter Processing Facility of the Kennedy Space Center, using many other elements of the Orbiter. Under no conditions were false signals like those seen on orbit reproduced. As of the date of this writing, the source of interference has not been located.

TABLE A-2.- STS 41-C MANEUVER SUMMARY

MNVR thrusters	TIG (MET) Planned Executed	Δ VTOT (FPS) Planned Executed	PEG 7 Δ VX (FPS) Planned Executed	PEG 7 Δ VY (FPS) Planned Executed	PEG 7 Δ VZ (FPS) Planned Executed	HA X HP (NM)
OMS-2 Both OMS	0/00:42:56.1 *	149.0 *	148.9 *	3.0 *	2.1 *	252 X 115
NC1 OMS left	0/05:17:57.7 0/05:17:57.7	11.3 11.4	11.3 11.4	0.0 0.2	0.1 0.2	251 X 121
NPC OMS left	0/06:57:35.4 0/06:57:35.4	9.3 9.4	0.0 0.0	9.3 9.4	0.0 0.1	251 X 121
NH2 OMS right	0/22:50:09.4 0/22:50:09.4	11.7 11.8	11.7 11.8	0.0 0.1	0.1 0.0	258 X 122
NSR Both OMS	0/23:34:53.0 0/23:34:53.0	231.0 231.1	230.5 230.6	0.0 0.0	15.4 15.4	258 X 255
LDEF SEP RCS + Z	1/03:25:00.0 1/03:25:00.0	0.5 0.5	0.5 0.4	0.0 0.0	-0.1 -0.2	259 X 255
NC2 RCS + X	1/07:40:01.1 1/07:40:01.1	1.5 1.5	1.5 1.5	0.0 0.0	0.0 0.0	259 X 256
NH2 OMS right	1/20:13:37.7 1/20:13:37.7	14.1 14.2	14.1 14.2	0.0 -0.1	0.1 0.2	266 X 258
NC3 Multiaxis	1/21:00:54.9 1/21:00:54.9	0.3 0.2	0.3 0.2	0.0 0.1	0.0 0.0	267 X 258
NCC Multiaxis	1/21:36:12.4 1/21:36:12.4	0.7 0.7	-0.2 0.1	0.0 0.1	0.7 0.7	267 X 258
TI OMS left	1/22:35:19.0 1/22:35:19.0	11.4 11.5	11.3 11.4	-1.1 -1.1	-1.3 -1.4	268 X 264
MC1 Multiaxis	1/23:01:25.0 1/23:01:25.0	* 1.0	* -0.3	* -0.1	* 0.9	*
PLANE NULL	NOT EXECUTED					
MC2 Multiaxis	1/23:30:55.0 1/23:30:55.0	* *	* *	* *	* *	*
MC3 Multiaxis	1/23:40:55.0 1/23:40:55.0	* *	* *	* *	* *	*
MC4 Multiaxis	1/23:50:55.0 1/23:50:55.0	0.1	0.1	0.0	0.0	*
Proximity operations						

*Data not available.

TABLE A-2.- Concluded

MNVR thrusters	TIG (MET) Planned executed	Δ VTOT (FPS) Planned executed	PEG 7 Δ VX (FPS) Planned executed	PEG 7 Δ VY (FPS) Planned executed	PEG 7 Δ VZ (FPS) Planned executed	HA X HP (NM)
SMM SEP 1 RCS + X	2/02:40:00 *	0.5 *	0.0 *	0.0 *	-0.5 *	*
SMM SEP 2 Multiaxis	2/02:50:00	0.8 *	0.8 *	0.0 *	0.0 *	*
NC4 RCS + X	2/17:03:55.2 2/17:03:55.2	2.5 2.4	-2.5 -2.4	0.0 0.0	0.0 -0.1	268 X 265
NC5 RCS + X	3/04:30:00.0 3/04:30:00.0	2.3 2.1	-2.3 -2.1	0.0 0.0	0.0 0.1	268 X 264
Start of second rendezvous						
NC6 OMS right	3/18:40:05.3 3/18:40:05.3	7.6 8.0	-7.6 -8.0	0.0 0.1	0.0 0.1	268 X 261
NCC Multiaxis	3/20:49:56.4 3/20:49:56.4	1.1 1.3	-1.1 -1.3	0.1 0.1	0.0 0.1	267 X 261
TI OMS left	3/21:49:03.0 3/21:49:03.0	5.6 5.8	5.6 5.8	0.1 0.1	-0.3 -0.6	268 X 264
MC1 Multiaxis	3/22:15:09.0 *	0.9 *	-0.3 *	0.0 *	0.9 *	*
MC2 Multiaxis	3/22:45:12.0 *	0.7 *	-0.3 *	-0.1 *	-0.6 *	*
MC3 Multiaxis	3/22:55:12.0 *	0.6 *	-0.4 *	-0.1 *	-0.4 *	*
MC4 Multiaxis	3/23:05:12.0 *	0.3 *	-0.3 *	-0.1 *	-0.1 *	
Proximity operations						
FSS test RCS + X	4/18:45:00.0 4/18:45:00.0	1.0 0.9	1.0 0.9	0.0 0.0	0.0 0.0	269 X 265
SMM SEP 1 Multiaxis	* 5/20:04:50.0	1.0 1.2	-0.2 -0.2	0.0 0.0	1.0 1.2	269 X 265
SMM SEP 2 Multiaxis	* 5/20:34:50.0	2.0 1.9	-2.0 -1.9	0.0 0.0	0.0 0.2	268 X 264
Deorbit BOTH OMS	6/22:31:30.0 6/22:31:30.0	460.4 460.8	-393.5 -393.5	0.0 -1.1	-239.0 -239.7	271 X 0

*Data not available.

D. STS 51-A was launched November 8, 1986/1215 GMT, with a crew of Hauck (CDR), Walker (PLT), Allen (MS1), Fisher, A. (MS2), and Gardner (MS3). After deploying two PAM-D payloads, the crew twice rendezvoused with PAM-D payloads (the Palapa and Westar) left in low orbits by injection failures following deployment from STS 41-B in February.

RNDZ profile is shown in figure A-7.

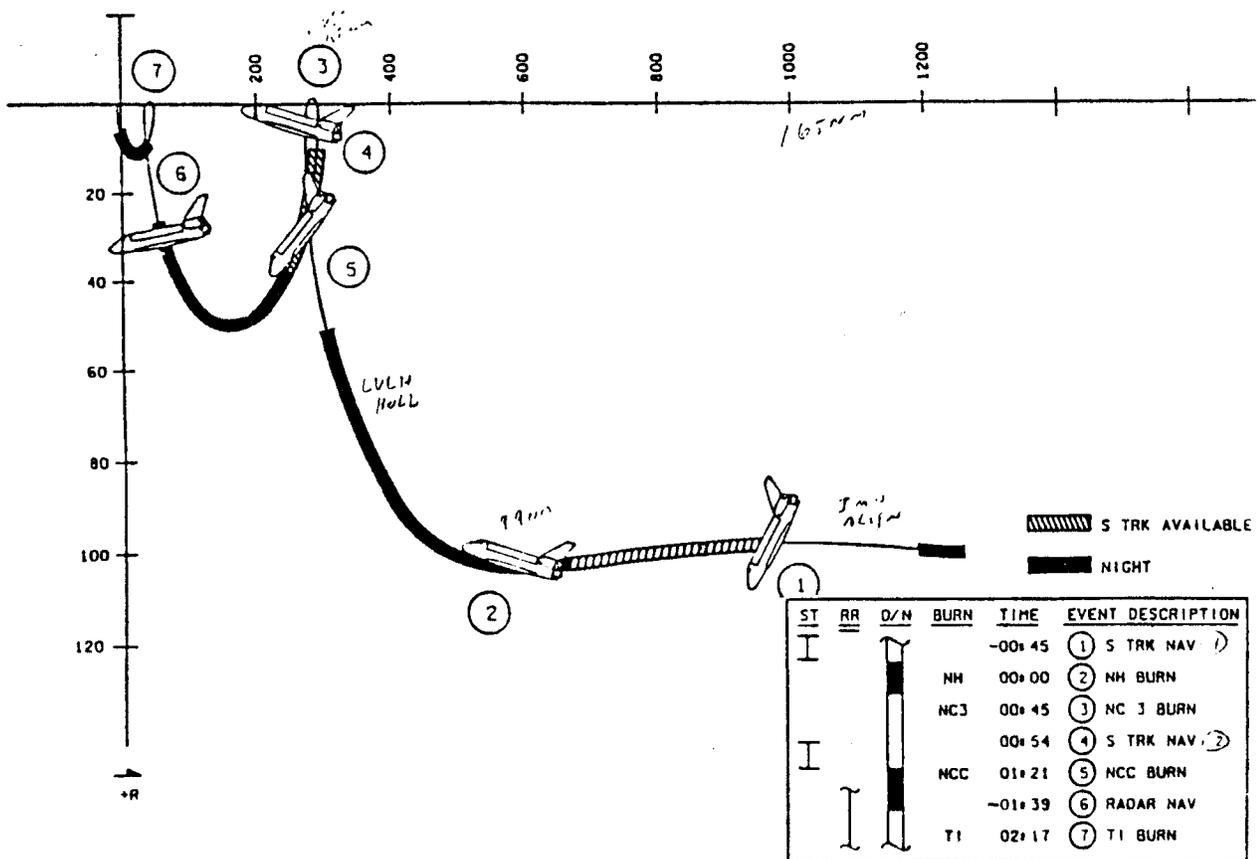


Figure A-7.- 51-A First RNDZ.

The DA8 "lessons learned" highlights these items.

- Spacecraft visibility was better than predicted. They were picked up in STRK at >100 n. mi. (used -Y tracker for first time).
- Deselect one IMU for STRK passes did smooth data.
- Stationkeeping at 35 feet eliminated plume disturbance concern. Used "normal" PRCS mode for translation adjustments. Used "low Z" mode from 200 feet to 35 feet. Did not use "low Z" for stationkeeping.

GENERAL

- Two deployables, two RNDZ's. These were unique RNDZ's since both satellites had to be deboosted from a higher orbit of different inclination. A phantom box was created for the RNDZ with the Orbiter and each satellite.
- Variable OMS-2 targeted to a phase angle at the circularization MNVR. The circularization MNVR was an arbitrary choice since there were more than 10 MNVR's between OMS-2 and NC3.
- NC1 biased posigrade (10 ft/s) for insertion dispersions.
- Circularize orbit morning of FD 2 for deployables.
- Backup separation burn was biased posigrade (6 ft/s) to ensure an adequate separation. Only two separation burns would be done; the third would be a phasing burn. Thus, the phasing burn could occur before or after either separation burn.

PALAPA RENDEZVOUS

- NPC scheduled sometime the afternoon of FD 3.
- NSR included to set lighting for terminal phase.
- NC2 biased posigrade (2 ft/s) to prevent going retrograde.
- Typical NH, NC, one-REV transfer to Ti. One-REV transfer to Ti dictated by the EVA requirement (crew workday).
- STRK pass prior to NH was questionable, due to acquisition range. This had the potential to be a one STRK RNDZ.

WESTAR RENDEZVOUS

- One-REV transfer to Ti. Again, this was an EVA constraint (crew workday).
- There was a potential for freezing of the fuel remaining in Palapa, which was an automatic jettison case. To prevent this from happening, used the -Y STRK in a generally Sun-facing attitude for STRK pass 1 (prior to NH). If additional Sun was required to keep Palapa warm, STRK pass 2 would be done with the -Y STRK. If even more Sun was needed, a Ti delay would be executed with the Orbiter in a solar inertial attitude. This was a very difficult thermal problem since the PAM ASE's could not be overheated.

- Westar and Palapa were supposed to be coplanar; they were not. We were lucky and were able to combine NC1-2 and NPC-2 (unscheduled MNVR) together and save fuel.

* * * *

The STS 51-A flightcrew report (March 28, 1985) made the following comments on RNDZ:

RENDEZVOUS

Crew Responsibilities

Because the PLT was to be very busy during the RNDZ MNVR's as the IV1 crewman (assisting the EVA crewmen in suit donning and checkout), the MS2 was assigned prime responsibility for assisting the CDR in executing the MNVR's. The CDR and MS2 had worked closely with the PROX OPS book procedures writer and felt very comfortable with the book. From the beginning of training it was baselined (as with all procedures which used on-orbit OMS or RCS fuel) that all MNVR's and burns would be set up and checked by two crewmembers. All of the 44 OMS and RCS MNVR's involved in RNDZ were executed this way with virtually no errors.

The OMS burns are single-axis burns performed under GPC control after a GPC-controlled maneuver to burn attitude. However, the RCS burns are primarily multi-axis burns which require manual inputs to the THC and are therefore more susceptible to errors in execution and slightly less efficient than automatic burns would be.

Recommendation: Incorporate in future software the capability to perform GPC-controlled RCS burns.

In OPS 201 the UNIV PTG display provides a maneuver completion time for all attitude maneuvers. In OPS 202 (the OPS mode for on-orbit burns) this information is not available. The crew was often concerned about initiating maneuvers to burn attitude early enough. The potential exists, due to the lack of data regarding maneuver completion time, that a more RCS-expensive maneuver mode (NORM vs. VERN), or rate, could be used by the crew for "insurance."

Recommendation: Incorporate maneuver completion time on the OPS 202 MNVR EXEC display.

STAR TRACKERS (STRK)

The STRK performance was excellent. All four attempts (two per RNDZ) at acquiring the satellites were successful at ranges of up to 120 miles. For each STRK pass, IMU3 was deselected to avoid the selection of filter-induced noise on the data which had occurred on STS 41-C. For the second STRK pass on each RNDZ, the STRK shutter had to be manually opened.

RENDEZVOUS RADAR (RR)

The RR performance was also excellent. Initial and solid lock-on for Palapa was 136 kft. Initial Westar lock-on occurred at 130 kft with solid lock-on at 120 kft. Good RR data was essential for mission success. Preflight data indicated that RR failure prior to first RNDZ associated with significant dispersions would have resulted in insufficient FRCS fuel to complete the second RNDZ.

Recommendation: Reevaluate risk to RNDZ mission success imposed by single string RR and non-interconnectable FRCS system.

Range rate and angular rate data were all smoother (less noisy) than that modeled in the SES.

Recommendation: Use flight data to improve the modeling of range rate and angular rate data in the SES.

TARGET VISIBILITY

Significant time and effort were spent in flight techniques meetings to determine the inertial attitude for the satellites to optimize the trade-off between STRK, RR, and visual acquisition. Worst case estimates were that the satellites might not be visible at 1 mile, the approximate range of the "manual" phase of RNDZ. The final decision was to optimize for STRK acquisition.

In fact, in this attitude the satellites were visible to the eye (acquired with the assistance of the COAS) at over 100 miles.

Recommendation: Feed back flight experience to update analytical models regarding visual acquisition of satellites.

MANUAL PHASE

The RNDZ manual phase begins at orbital sunrise when the TGT is around 1 n. mi. distant. It is the point at which the CDR begins to make manual control inputs to the THC and RHC to ensure Orbiter intercept of the extension of the TGT V-BAR 300 to 400 feet ahead of the TGT with reasonable closure rates. With good RR information, this phase was completed without incident per the published procedures.

PROXIMITY OPERATIONS PHASE

After arrival on the V-BAR, subsequent braking MNVR's were performed as published. On both approaches low Z mode was selected on the DAP at a 250- to 270-foot distance to avoid pluming the satellite with the upward firing jets of the Orbiter. This mode uses approximately nine times the fuel for +Z (or braking) MNVR's than when not in low Z, and thus use of +Z inputs to the THC were minimized during this period. On the first RNDZ (Palapa), several out-of-plane (+ or -Y) inputs were made while in low Z mode to correct a lateral offset (10 to 15 feet to port), which would have brought the RMS too close to the satellite. Shortly thereafter the closure rate was observed to increase from the planned 0.2 ft/s to 0.5 ft/s. After using +Z low Z firings to bring closure rate back to 0.2 ft/s, a subsequent increase in closure rate was again observed and then compensated for. Previous flight results have suggested that the firing of Y jets while in low Z may cause a resultant increase in net propulsive effect in the minus Z direction. The flight results tend to confirm that theory. On the second (Westar) RNDZ, the use of Y inputs during low Z operations was minimized and the -Z acceleration effect was not observed.

Recommendation: Analyze the normal jet firing history and RR data to attempt to establish the source of the undesirable -Z acceleration during low Z maneuvering.

Upon reaching 60 to 70 feet separation from the TGT's (at about the same time RR broke lock), low Z mode was deselected, and final braking to the 35-foot stationkeeping position was effected. Both RNDZ profiles resulted in attaining a stationkeeping position approximately 5 minutes past the preplanned time, orbital noon. This did not cause problems since all of the other procedures were nominal and the timing was not critical.

Recommendation: When tracking data indicates that RNDZ dynamics will result in late arrival in the stationkeeping position, and if Sun angle is critical to establishing that position, procedures should be available to adjust the braking gates to compensate.

STATIONKEEPING

Early in the development of the retrieval mission, the fact that the HS 376 satellites are unlit and have limited high-reflectivity surface caused concern about nighttime stationkeeping at 200 feet, which had been baselined on the two previous missions involving stationkeeping. Parallel efforts were initiated to provide enhanced lighting from the Orbiter as well as to investigate close-in stationkeeping. The lighting effort resulted in the manifesting of the Streamlight One Million (1 million candlepower) handheld spotlight, which showed the greatest promise of providing adequate illumination from inside the Orbiter.

"Night stationkeeping on the HS-376 satellite posed an additional challenge to the flight design. During the first Shuttle formation flying on STS-7, the TGT satellite was equipped with battery-powered running lights. The Orbiter was flown at ranges up to 1000 feet from the satellite. Visual tracking of the satellite at night at these distances was not a problem. During the Solar Maximum satellite repair mission, 300-foot stationkeeping was baselined. Even though the Solar Maximum satellite was not equipped with running lights, the large amount of gold-colored, multilayer insulation provided adequate reflection of Orbiter payload bay lights to permit stationkeeping at 200 feet through the night passes. However, the low reflectivity of the HS-376 satellites when viewed from all aspect angles, except from the top, caused serious concern about the crew's ability to maintain visual contact during night stationkeeping.

To relieve this concern, parallel efforts were initiated: the first, to manifest onboard a high-intensity (1 million candlepower) spotlight, and the second, to investigate the feasibility of stationkeeping at greatly reduced separation. As stated, all previous stationkeeping had been done at distances of 200 feet or greater to preclude disturbing the TGT satellite with reaction control jet plumes. A development effort was initiated to determine the feasibility of conducting long-term (more than 30-minute) stationkeeping with 35-foot lateral separation from Orbiter longeron sill to satellite.

A side benefit which could be realized by this configuration would be that the flight of the MMU to capture the satellite would be of much shorter duration, significant because the MMU cold gas fuel budget did not leave large reserves. But the use of the untethered MMU in close proximity to both the Orbiter and the satellite introduced another potential complication. Concern was expressed about failure modes of the MMU, which would necessitate maneuvering of the Orbiter to either rejoin a dormant MMU, or to chase an MMU which had experienced a failed-on thruster and was thus moving rapidly away from the Orbiter. With the satellite free flying directly adjacent to the envelope of the Orbiter payload bay, it was feared that the Shuttle pilot would be severely restricted in his maneuvering volume, and thus might either collide with the satellite or be unable to rejoin the failed MMU within the limits of the RCS fuel budget."

A series of simulations was initiated to evaluate the implications of these concerns. The flightcrew used the SES, which modeled the RCS jet plume, to evaluate the piloting tasks associated with 35-foot stationkeeping. RCS fuel data were generated for long-term stationkeeping and for a variety of MMU rescue scenarios. At the same time, various analyses were done offline to evaluate the effect of various levels of plume forces on the stability of the rotating satellite. The net results of all of the simulations encouraged the decision to proceed with the close-in (35-foot) stationkeeping for the following reasons:

TABLE A-3.- 51-A SUMMARY

FLIGHT/SIM TEST ID	DATE				ORB	CONSOLE POSITION				PAGE
TIME	FLIGHT EVENTS/HISTORY/BRIEFING *EXCLUDED									
	CY6 RND=				RND= R C =					
	ΔV_x	ΔV_y	ΔV_z	ΔV_e	ΔV_x	ΔV_y	ΔV_z	ΔV_e		
CNC-2	176.6	176.6	0	0	*177.1	176.4	7.1	14.4		
NC1	10.0	10.0	0	0	*8.9	8.9	-1	.1		
HL	5.8	5.8	0	0	*2.9	2.9	0	0		
CIR	13.4	13.3	0	-1.8	*12.8	12.8	0	.2		
SEP1	11.1	10.6	0	-3.0	*11.0	10.6	-0.3	-2.8		
SEP2	15.0	14.4	0	-4.1	*15.2	14.6	0.3	-4.2		
NPC	0	0	0	0	*2.4	0	2.4	0		
SEP3	6.0	6.0	0	0	*4.0	4.0	0	0		
USR	16.5	14.6	0	7.7	*31.5	30.8	-1	-6.7		
NC2	2.0	-2.0	0	0	*2.6	2.6	0	0		
NH	27.9	27.9	0	0	*22.5	22.5	-1	-3		
NC3	14.7	14.7	0	0	*12.0	12.0	-1	0		
TI	11.6	11.6	0.1	-0.2	*9.6	9.5	1.4	0.6		
..	:	:	:	:	:	:	:	:		
RND 1 TOTAL	310.6				312.5					
NC1-2	15.7	-15.7	0	0	*15.3	-13.9	-6.5	0		
NPL-2	0	0	0	0	*0	0	0	0		
NC7-2	0	0	0	0	*.2	.2	0	-1		
NH-2	.2	-.2	0	0	*.9	-.9	0	.1		
NC3-2	.1	-.1	0	0	*3.6	3.6	0	-1		
TI-2	11.9	11.9	0	-.2	*10.5	7.9	.4	7.0		
RND 2 TOTAL	27.9				20.5					
TOTAL	338.5				343.0					

- Fuel usage for the formation flying task was found to be on the same order as that used for 200-foot stationkeeping. There was, in fact, an added RCS fuel saving of not having to expend energy to stop Orbiter relative motion at 200 feet and then reinitiate the closure rate for final join-up on the mated MMU and satellite.
- The shorter flyover distance for the MMU allowed more time to be spent on the other EVA tasks.
- Rescue of the failed MMU was actually enhanced. All of the MMU operations were conducted close to the Orbiter, and MMU failures were therefore detected more rapidly by the onboard crew. Corrective actions were more quickly transmitted to the MMU pilot (who was often unaware of the MMU failure). Transit distances to the failed MMU were decreased; therefore, orbital mechanics effects on the relative motion of the Orbiter and satellite had less time to propagate. Use of a simple sidestep or pitch-up maneuver by the Orbiter pilot resolved concerns about satellite collision. With a limited number of failure scenarios exercised, Orbiter fuel usage appeared to be less than for the 200-foot stationkeeping task.
- Off-line simulations indicated that by using the standard Orbiter braking profile in to 35 feet, very little energy was transferred to the satellite.

Flight evaluation of the close-in stationkeeping configuration was very positive, with Orbiter fuel usage on the order of preflight predictions. Orbiter RCS plume did not cause any apparent upset to the motion of the satellite.

- E. In early 1985, John Cox (DA8) presented this compilation of Orbiter rendezvous and PROX OPS experience to a conference on rendezvous.*

* Rendezvous and Proximity Operations Workshop, February 19-22, 1985, Kenneth J. Cox, workshop organizer, NASA Johnson Space Center, Houston.

1. RNDZ profile is well behaved. The phasing must accommodate other flight plan activities and be within propellant budgets - hence all profiles will be customized to some extent. Multiple RNDZ considerations imply traffic management in future Space Station/OMV/Orbiter operations.
2. Breakout MNVR planning is necessary. Planning should be based upon propellant quantities available and projected usage to complete the RNDZ sequence, especially once the intercept is initiated. Breakout planning is necessary for future RNDZ activities with Orbiter/Space Station/other satellites/OMV.
3. If PL plays an active role in performing RNDZ/PROX OPS sequence, then it should consider carrying a responsibility to perform a non-RF activated breakout MNVR.
4. Propellant quantity will always be a premium. Orbiter forward RCS is most limiting for PROX OPS.

5. RNDZ operations to date have all had excellent performance from NAV sensors, hence operations appear to be standardized. Failure modes and dispersed trajectory conditions have not yet been encountered.
6. Crew control of payload attitude eases RMS or MMU capture task.
7. PROX OPS will tend to be custom designed for each PL. PL flexibility will go a long way in stabilizing this area (e.g., RMS grapple fixture, hand holds, retractable appendages, cooperative TRK, attitude control capability/maneuverability).
8. Contamination evaluation is required for specific payload and specific PROX OPS technique.
9. Plume disturbance susceptibility of each payload must be well understood for PROX OPS design. If susceptibility is significant, then alternate recovery schemes should be developed.
10. Lighting is a significant factor in completing a RNDZ/PROX OPS sequence. Sunlight (direct or reflected) can blind crewmembers or cause TV cameras to "bloom," etc. Insufficient lighting requires close-in stationkeeping to keep TGT in sight during dark passes.
11. Caution should be taken when using visual relative motion cues for stationkeeping. Unexpected target motion (notably in darkness) may result in higher than expected propellant consumption ("simple" stationkeeping can easily become a flyaround, especially if plume impingement is not well analyzed).
12. Propellant reserves to cover rescue of an MMU are considerably higher for the three-body problem (collision avoidance) than for the two-body.
13. Since each retrievable PL will specify different contamination requirements and will offer a variety of profiles, surface areas, and moments of inertia, and will be controlled in attitude and translation by a variety of means, then consideration should be given to providing a flexible retrieve interface that will allow capture by a primary and a backup method. This applies to Orbiter, OMV and Space Station capture activities.
14. Large mass PL's can be man-handled with relative ease, provided the problem has been thought through in advance, and if suitable handholds are available.
15. High fidelity man-in-the-loop simulation is crucial in technique development and operating training.

(TARGET AT CENTER OF ROTATING LVLH REFERENCE FRAME)

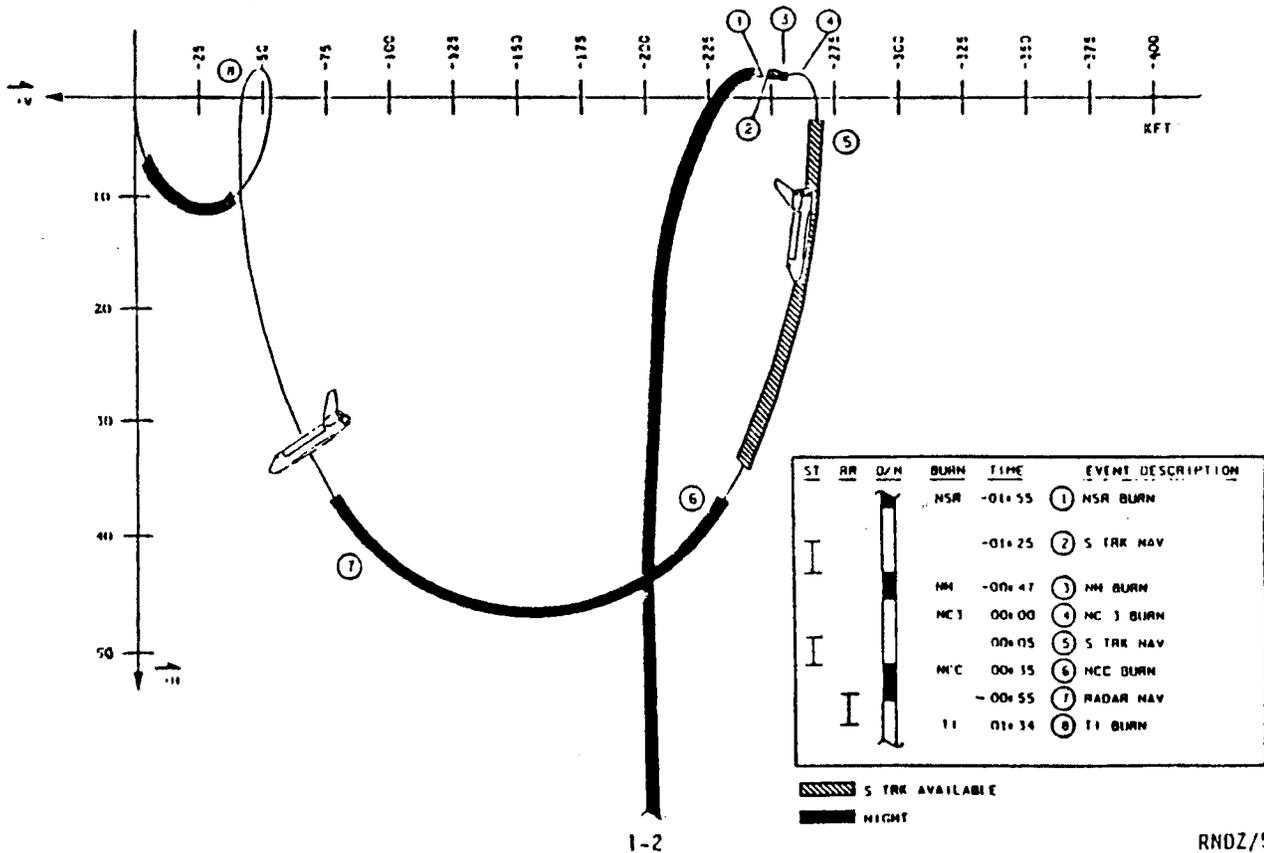


Figure A-8.- 51-D RNDZ profile.

F. STS 51-D was launched April 12, 1985/1359 GMT with a crew of Bobko (CDR), Williams (PLT), Seddon (MS1), Griggs (MS2 and EVA1), Hoffman (MS3 and EVA2), Walker, C. (PS1), and Garn (PS2). Following deployment, the Syncom F-2 satellite failed, and the crew performed an unplanned RNDZ in an attempt to activate the payload.

The RNDZ profile is shown in figure A-8.

The following comments from the 51-D flightcrew report describe their RNDZ and PROX OPS:

It had been approximately 9 months since the crew completed RNDZ training associated with a SPARTAN PL. The complete cycle of RNDZ and PROX OPS training (about 115 hours of SMS, SES, classroom, RMS), less integrated sims, had been accomplished. No RNDZ or PROX OPS training had been performed since that time. None of the flight data file procedures were onboard.

A rather lengthy teleprinter message was sent up containing most of the nominal RNDZ procedures and cue cards. The crew constructed two FDF RNDZ books using the postinsertion books, the teleprinter message, scissors, and tape. Having a book which looked like the procedures used in previous training was invaluable during conduct of the actual RNDZ. Also, cue cards were constructed, approximating the size and shape of the real cards, using kneeboard cards and Velcro from the IFM kit. These were positioned in their nominal locations.

Fortunately, all of the onboard hardware performed flawlessly. An ST lock-on was obtained prior to going to TGT track. Within three NAV cycles, the angles were very small, and over 100 ST marks were obtained. The RR locked on at approximately 158,000 feet, which seemed to be the maximum number that could be displayed on SPEC 33. Orbit targeting for RNDZ burns was nominal, and the midcourse correction burns were very small, an indication that the NAV states had converged rather well.

RNDZ was performed by the CDR and PLT with MS1 cross-checking and plotting position and velocity on a hand-built graph. This technique had been developed during previous training. The how-goes-it plot maintained by MS1 was very important as a cross-check of targeting.

RNDZ ended with the Orbiter being well-placed for PROX OPS. With no reason to hurry, the approach to the stationkeeping position at 35 feet was done slowly, allowing minimum fuel usage and minimum control inputs. MCC noted that with the approach speed that had been established, closure to 35 feet would not occur before sunset. Closing rate was increased slightly in order to arrive at the 35-foot stationkeeping position by sunset. Low Z DAP was entered at 200 feet, but little change in the closure rate had to be made before the 60-foot point, and little cross-coupling was observed between the attitude control and the closing rate. At 50 feet, normal Z was again selected, and a stationkeeping position was established at 35 feet.

During the final approach phase, which occurred just before going into darkness, the Sun was a significant factor. The sunset was right behind the Syncom, and that made seeing the Syncom difficult and the CCTV useless. Once in the darkness, with the Syncom within 50 feet of the PLB, it was easily seen by the illumination of the PL bay lights, and the CCTV again was a good ranging device. If a RNDZ must be accomplished when the Sun is a factor, provisions for blocking the Sun should be made.

During the night pass, stationkeeping position was easily flown. After going back into sunlight, a flyaround was performed to enable Syncom to be stable with respect to the Orbiter during RMS operations. The flyaround was done using an AUTO MNVR to an inertial attitude with the Syncom still at 35 feet. In the previous Spartan training, the flyaround was performed at 300 feet - just outside the contamination sphere. The 35-foot position was not a difficult procedure, and would have been even easier if it had been practiced during simulations. In the case of this

TABLE A-4 - STS 51-D MANEUVER SUMMARY

MNVR Thruster	TIG (MET) Planned Executed	ΔV_{TOT} (FPS) Planned Executed	PEG 7 ΔV component (ft/s)			HA x HP (NM)
			ΔV_x Planned Executed	ΔV_y Planned Executed	ΔV_z Planned Executed	
OMS-2 Both OMS	0/00:43:21.5 0/00:43:21.5	228.3 228.6	228.2 228.4	0.1 - 1.1	8.4 10.0	249 x 160
SEP-1 Right OMS	0/09:54:25.0 0/09:54:25.0	11.0 11.1	10.6 10.7	0.0 0.2	- 3.0 - 3.0	249 x 167
SEP-2 Both OMS	1/01:14:16.0 1/01:14:16.0	15.0 *	14.4 *	0.0 *	- 4.1 *	250 x 174
Inverse SEP Both OMS	1/02:46:44.4 1/02:46:44.4	15.0 *	- 14.4 *	0.0 *	4.0 *	249 x 167
Phase adjust +Z RCS	1/09:57:00.0 1/09:59:00.0	2.4 2.4	2.4 2.4	0.0 0.0	- 0.0 - 0.3	249 x 167
Phase adjust +Z RCS	3/06:36:00.0 3/06:36:35.0	1.8 1.6	1.8 1.6	0.0 - 0.2	- 0.0 - 0.2	249 x 166
Phase adjust +Z RCS	3/18:54:00.0 3/18:54:00.0	1.7 1.9	1.7 1.9	0.0 - 0.0	0.0 - 0.0	250 x 166
Coelliptic Left OMS	4/06:43:00.0 *	10.8 *	1.2 *	0.0 *	- 10.7 *	249 x 167
NC3 Left OMS	4/19:29:20.0 4/19:29:20.0	11.5 11.6	- 11.5 - 11.6	0.0 0.1	0.0 0.1	243 x 167
NCC Multiaxis	* 4/20:02:42.0	* 0.9	* 0.8	* 0.0	* - 0.4	243 x 167
TI Left OMS	* 4/21:01:30.0	* 8.7	* 8.0	* - 0.6	* - 3.5	247 x 167
MC1 Multiaxis	* 4/21:27:42.0	* 1.4	* - 0.6	* - 0.2	* 1.2	*
Plane null Multiaxis	* 4/21:38:06.0	* 0.2	* 0.0	* - 0.2	* 0.0	*
MC2 Multiaxis	* 4/21:57:26.0	* 1.3	* - 0.6	* - 0.1	* 1.1	*
MC3 Multiaxis	* 4/22:07:26.0	* 0.2	* - 0.2	* - 0.1	* 0.1	*
MC4 Multiaxis	* 4/22:17:26.0	* 0.3	* - 0.1	* 0.1	* - 0.3	*
SEP-3 Low Z	* 5/00:20:07.0	* 0.9	* 0.9	* - 0.0	* - 0.1	249 x 168
SEP-4 Multiaxis	* 5/00:24:00.0	* 1.9	* 0.0	* - 1.9	* - 0.1	249 x 168
SEP-5 Left OMS	* 5/00:39:00.0	* 20.3	* 20.3	* 0.3	* 0.1	249 x 179
Deorbit Both OMS	6/22:45:20.0 6/22:45:20.0	451.5 *	- 279.6 *	320.8 *	-158.8 *	245 x 18

*Data not available.

flyaround, the crew did not know how much time the maneuver would take, or even which way it would go, prior to commencing the maneuver.

Final positioning of the Syncom took longer than expected, since again there was no good "sight picture" from ground simulations. Once the Syncom had been positioned over the starboard longeron, the Orbiter was very stable. No control inputs were made during the first three or four operations with the "fly swatter." The crew was surprised when the motion of the satellite towards the cockpit occurred, caused by the swatter dragging on the Syncom and impacting the lever.

Considering the time since the crew had last trained for RNDZ and PROX OPS, everything went extremely well. Of course, all of the sensors and everything on the Orbiter worked perfectly, but the success of the operation still indicates the training was thorough and the procedures mature.

- G. STS 51-G was launched June 17, 1985/1133 GMT, with a crew of Brandenstein (CDR), Creighton (PLT), Lucid (MS1), Nagel (MS2), Fabian (MS3), Baudry (PS1), and al Saud (PS2). After deploying a number of commercial PL's, the crew deployed and then retrieved the Spartan free-flier.

The 51-G mission had originally been planned to conduct the LDEF retrieve, described in section 5.3.2.3 of this handbook.

The Spartan RNDZ profile is shown in figure A-9.

Crew comments on Spartan RNDZ, STS 51-G (based on interview with J. O. Creighton about a year and a half after the mission) are as follows:

The actual flying was done by the CDR, and it was similar to the training except that visibility was much easier in the real world. The RNDZ was straightforward (the crew had originally trained for the LDEF retrieve and felt confident with the R-BAR approach), and the V-BAR approach went well.

For separation, the PL hung rock steady, "almost disappointing." During initial release, crew made maybe one or two taps on the THC, maybe even none. They backed away using about 10 +Z pulses. They planned to shoot for about 400 feet before performing the +X separation, and were concerned to be well away from the PL at that point. The RR picked it up quicker than in sims: in real life they had lock-on at 150 to 200 feet while in sims it was usually 300 to 400 feet. The RR tracked out quite a long distance and in fact never lost lock; the crew had to break lock finally.

For retrieval, the crew saw the PL visually a long, long way out. During an STRK pass at 150 kft, they could see the PL in the COAS. The burns and targeting went a lot better than in simulators. The radar, far out, would break track, and then later get solid. MDM FA3 went out.

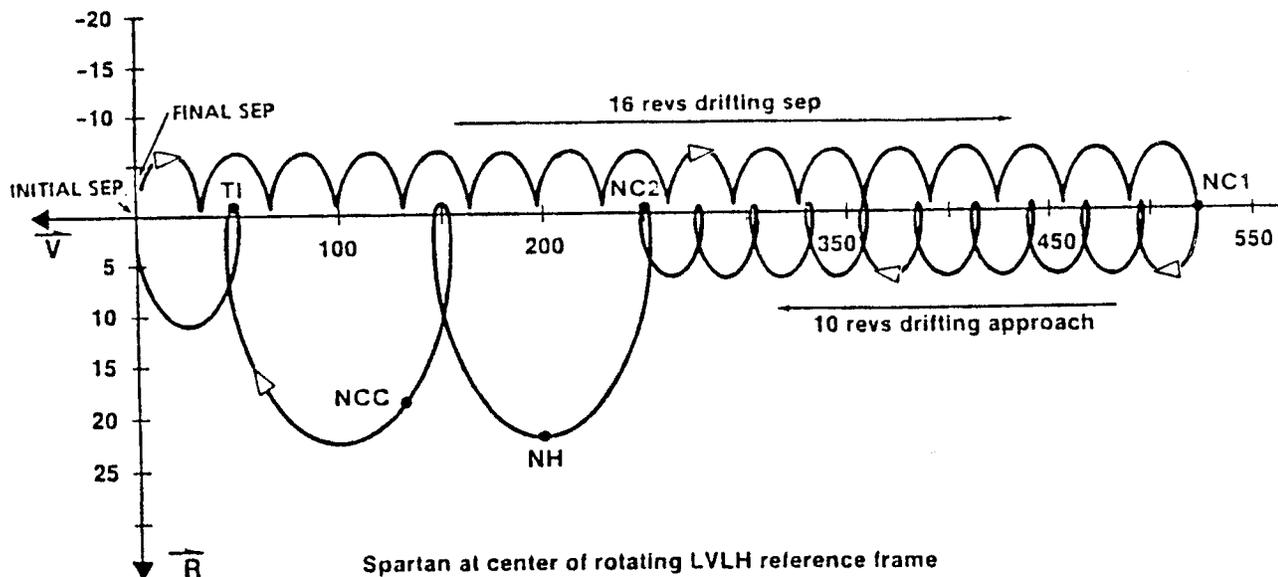


Figure A-9.- 51G Profile (Spartan)
(scale in kilofeet).

Regarding training for "no radar" case, the CDR felt it could have been done, but would have been "sporty." The difficult region is not close in, but the problem is out at 6000 to 7000 feet on the way up to the V-BAR, especially in not knowing range rate in this interval.

The crew noticed that with low Z, the closing rate increased when doing other accelerations, and these had to be broken off, or uncomfortable rates would build up.

When close, they saw that the spartan had a bad attitude. Upon getting very close in (with the PL in mid-bay just above the sill, quite a bit closer than the planned 35 feet), they used the arm to reach around to the grapple fixture, which was on top, and on the opposite side from the RMS. The crew felt that the closer the PL, the easier the flyaround.

The crewmembers all wrote individual reports within a month of the mission, but they were never assembled. CDR covered PROX OPS and MS2 covered the RNDZ. Those manuscripts are unavailable.

TABLE A-5.- STS 51-G MANEUVER SUMMARY

MANEUVER		TIG (MET)	ΔV_T (FPS)	ΔV_X (FPS)	ΔV_Y (FPS)	ΔV_Z (FPS)	HA(NM)	HP(NM)
MPS DUMP	Planned	0/00:10:30	8.9	8.0	0.0	4.0	189	35
	Actual	0/00:09:52	12.9	12.5	-1.0	-3.1	192	34
OMS-2	Planned	0/00:40:36	278.7	276.9	0.0	31.5	192	190
	Actual	0/00:40:29	278.2	275.5	-0.1	38.6	192	190
MORELOS SEP	Planned	0/08:19:51	11.0	10.6	0.0	-3.0	196	192
	Actual	0/08:19:51	11.1	10.7	0.2	-3.1	196	192
ARABSET SEP	Planned	1/02:38:56	11.0	10.6	0.0	-3.0	202	192
	Actual	1/02:38:56	11.1	10.8	0.1	-2.9	202	192
TELSTAR SEP	Planned	2/00:02:36	11.0	10.6	0.0	-3.0	208	192
	Actual	2/00:02:36	11.1	10.7	0.1	-3.1	208	192
SPARTAN SEP 1	Planned	3/04:35:01	1.0	0.0	0.0	-1.0	208	192
	Actual	3/04:35:01	1.1	0.0	-0.1	-1.1	208	192
SPARTAN SEP 2	Planned	3/04:50:01	2.0	2.0	0.0	0.0	208	193
	Actual	3/04:50:01	1.9	1.9	0.0	-0.1	208	193
NC1	Planned	4/05:22:42	5.1	-5.1	0.0	-0.1	207	191
	Actual	4/05:22:42	5.3	-5.3	0.0	-0.2	207	191
NC2	Planned	4/20:41:58	2.4	-2.4	0.0	0.0	207	190
	Actual	4/20:41:58	2.6	-2.6	0.0	0.0	207	190
NCC	Planned	4/22:48:24	0.8	0.3	-0.4	-0.7	207	190
	Actual	4/22:48:24	0.9	0.5	0.1	-0.7	208	190
TI	Planned	4/23:45:48	3.7	1.7	-0.4	-3.3	207	191
	Actual	4/23:45:48	3.4	1.8	-0.3	-2.9	207	191
MC1	Actual	5/00:10:00	0.22	0.08	-0.18	0.09		
MC2	Actual	5/00:38:48	2.5	-0.23	2.35	-0.76	(TIGSLIP 4 ^{M24S})	
MC3	Actual	5/00:48:48	0.24	-0.21	0.04	-0.10		
MC4	Not performed							
ORB ADJ	Planned	5/04:45:00	100.0	-100.0	0.0	0.0	192	150
	Actual	5/04:45:00	100.2	-100.2	0.1	-0.1	192	150
DEORBIT	Planned	7:00:34:30	279.3	-233.8	0.0	-153.0	194	0
	Actual	7:00:34:30	279.6	-234.1	-0.1	-153.0	194	0

- H. STS 51-F (Spacelab 2) was launched July 29, 1985/2100 GMT, with a crew of Fullerton (CDR), Bridges (PLT), Henize (MS1), Musgrave (MS2), England (MS3), Acton (PS1), and Bartoe (PS2). Major activity involved solar observations. A subsatellite, the Plasma Diagnostic Package (PDP), was deployed for a series of precise formation flying MNVR's, and was then retrieved.

Sample PROX OPS MNVR with the PDP are shown in figure A-10.

The STS 51-F flightcrew report (December 3, 1985) described PROX OPS this way:

PROX OPS with the PDP were timelined for FD3 for a period of 9 hours and 30 minutes between MET times of 2/2 + 00 and 2/11 + 30. A summary of the preflight plan follows:

Release the PDP from the RMS, back out along the V-BAR to 300 feet; stabilize, perform a 720° Orbiter roll; restabilize; fly around the PDP three times at ranges to approximately 1500 feet maximum; cross the V-BAR in each revolution in plane to fly a wake transit; fly two additional wake transits after the third revolution; and make a standard approach and grapple.

The objective of the flyarounds was to fly through points in space which placed the Orbiter and PDP on the same magnetic field line (flux tube connection) twice during each revolution, with a desired accuracy of ± 29 feet from the preflight specified point at the specified time ± 1 minute. Hitting the flux tubes required an out-of-plane MNVR. After crossing the lower flux tube, a MNVR back into plane was required to perform the wake transit. The objective of the wake transit was to fly in plane from 25° below the V-BAR to 25° above the V-BAR at various ranges from 200 to 800 feet.

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The procedures developed to accomplish these objectives required a total of 27 RCS burns. The burns were targeted using the standard Orbiter software for Lambert targeting via the ORBIT TGT display. Manual MNVR's were developed for the 720° roll, and the final return to the V-BAR. Based on SES/SMS development runs, the burns had to be trimmed to ≤ 0.1 ft/s to achieve the desired accuracies. Fuel margins were predicted to be tight.

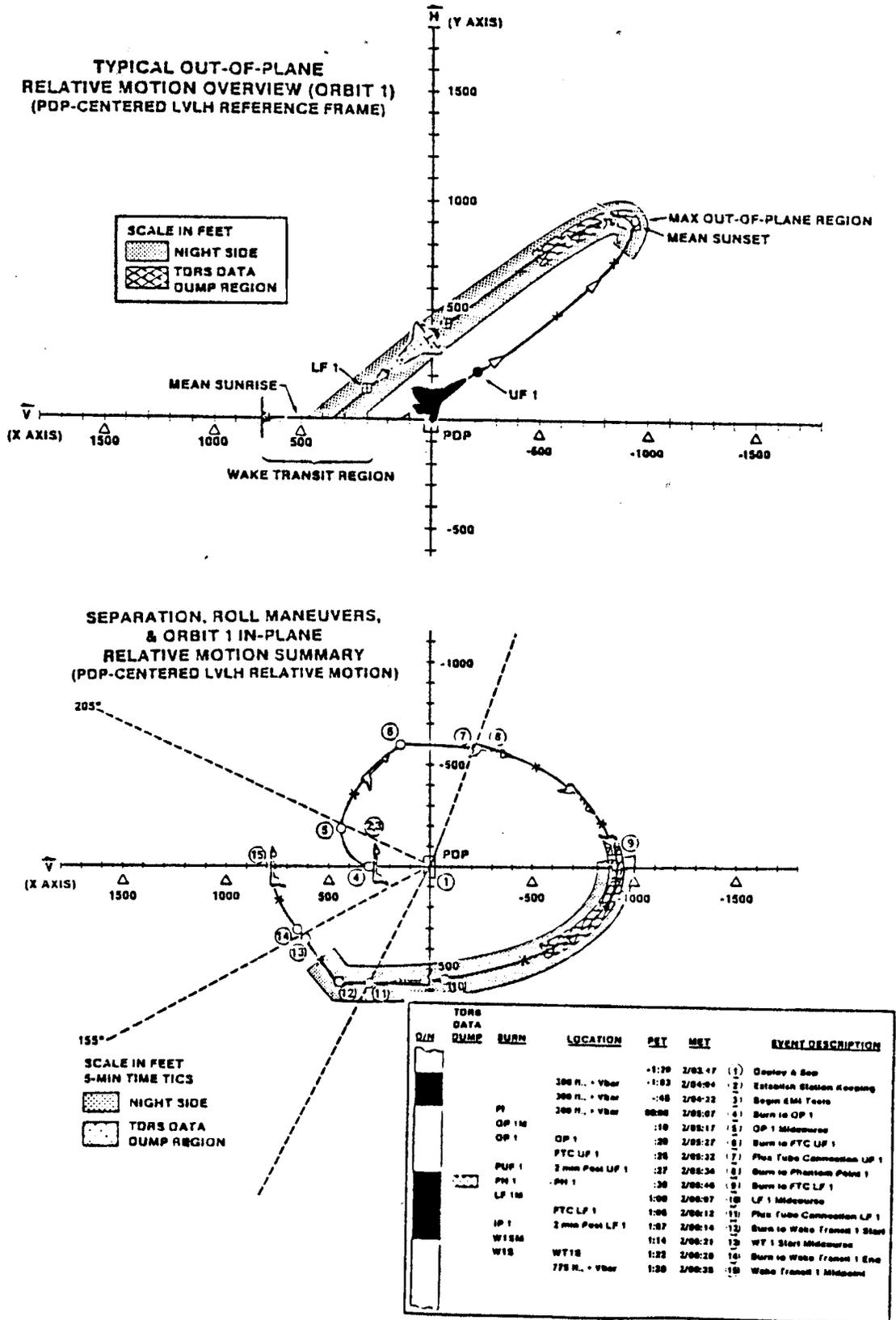


Figure A-10.- PROX OPS maneuver with PDP.

The concept of crew operations developed in training was used in flight, and worked well. The blue shift was on duty at the beginning of the phase. Also the CDR aligned his sleep schedule with the blue shift until after the phase. The PLT, nominally on the red shift, was awakened early for this activity at 2/00 + 30. The PLT and MS2 occupied the forward seats for the entire phase and shared the NAV, targeting, and propellant monitoring operations. The CDR occupied the aft starboard station and performed all manual maneuvering and RCS burns. The blue shift MS and PS handed over to the red shift MS and PS, approximately halfway through the phase. The MS operated the RMS and CCTV and assisted the PS with science operations and manual data recording. The PS conducted the science operation and performed the still and 16mm photographic documentation for both science and PAO requirements.

All PROX OPS crew activities including science experiment activities were integrated into the PROX OPS checklist, which was a very mature document by launch day. The document contained both the nominal FD3 timeline, a backup FD6 timeline, and numerous contingency timelines for FD3 and 6. The primary contingency procedures covered the loss of the RR and a shortage of fuel or start delay, which would necessitate dropping one or more revolutions of the flyaround.

The PROX OPS phase was basically flown as timed preflight, with two exceptions caused by the lower orbit and fuel state due to the ATO pre-MECO dump. The low orbit required a 30-minute earlier start time for the PROX OPS, and the third flyaround was deleted because of limited fuel. The PROX OPS checklist accommodated these changes within the preplanned contingency procedures with very few flight notes.

Flux tube miss distances of 40, 68, 47, and 16 feet were achieved, typical of the best accuracies seen in training and close enough to achieve all science objectives. Total fuel usage was slightly higher than preflight predictions. The predicted fuel for the flown profile was 642 pounds forward and 989 pounds aft, with standard deviations of 43 and 75 pounds, respectively. Actual fuel usage was 744 pounds of forward and 1053 pounds of aft fuel.

Two items were noted which may explain the higher fuel usage. First, stabilizing on the V-BAR at 300 feet after the release of the PDP was more difficult, and took longer than anticipated. Second, the RCS burns were not easily trimmed to ≤ 0.1 ft/s. There was a significant instability in the response of VGO's following a translation pulse input that was very similar to that seen in the SMS. This characteristic made it difficult to make "clean" MNVR's, and a few small inadvertent overshoots definitely caused higher fuel usage. There is no doubt that the entire system was pushed to the limits of its accuracy.

The performance of the RR appeared identical to the models used in training. There was considerable noise in both the displayed range and range rate data; however, it did not appear to affect the NAV adversely. Over 2000 marks were incorporated during the phase without a rejection.

The PDP was stable at release except for a very slight wobble of approximately $\pm 1^\circ$. The wobble was attributed to a slight misalignment between the spin axis of the reaction wheel and the ROT axis of the PDP. Except for this slight wobble, which was of no concern, the PDP was rock solid at grapple. The PDP was found in exactly the same attitude in which it had been released, with no observable residual roll rate. There was not the slightest effect of plume impingement noted.

Visibility of the PDP at night was satisfactory, using its running lights only. Reflectors had been added to the PDP to aid in night visibility. These were evaluated with the flashlight at close range and worked well. Neither the flashlight nor the docking light produced observable light from the reflectors at ranges of 1000 to 1500 feet. The Streamlight was not evaluated.

The long, handheld parallax rangefinder was briefly evaluated. The rangefinder indicated a range of 1100 feet when the radar indicated 1000 feet.

In summary, if the crew were to fly this phase of operations again, it would be done the same way. The importance of the highly developed, integrated checklist and the extensive, high-fidelity crew training to the success of these activities cannot be overemphasized. Success depended on zero errors, and that required extensive preflight preparation. The level of concentration required was intense, both in training and flight. The concept of using the PLT and MS2 to check each other during the hundreds of keystrokes required for targeting and navigation was considered essential to assuring the zero error performance.

* * * *

The following excerpt is from the DM5 "STS 51-F Post Flight Report" by M. Veres, March 18, 1986:

1. Procedures development for the STS 51-F PROX OPS presented several unique challenges. In addition to the usual close coordination within the JSC community, it was also necessary to coordinate with several elements of the Marshall Space Flight Center, and occasionally with the scientific investigators directly. This high level of integration was necessary because, at various times, all seven crewmembers were involved in some aspect of the PROX OPS, the basic purpose of which was to hit a series of predetermined points relative to the PDP, known as flux tubes and wake transits. A flux tube connection occurred when the Orbiter and the PDP were aligned on the same geomagnetic field line. A wake transit was induced by flying the Orbiter directly in front of the PDP at the desired range. This was accomplished by returning the Orbiter to the orbit plane of the PDP at a point 25° below the +V-BAR, and continuing to fly in plane to a point 25° above the +V-BAR. An unprecedented degree of accuracy was required to hit the flux tubes, both in terms

of position and time, while performing a series of scientific operations which were keyed to major events in the PROX OPS.

2. Two major types of techniques were developed to accomplish the science objectives. The primary technique, known as "AUTO/NAV targeting" was developed by N. Tursa and D. Dannemiller. Most of their work focused on optimizing transfer times and the placement of burns. Certain orbit targeting constants were also changed to permit short (typically 15 minute) transfer times. NAV analysis by M. D. Luneau led to changes in the NAV I-loads, which not only allowed extremely accurate NAV at unprecedented close ranges, but now has become standard for all flights.
3. The second technique, known as "manual targeting," was developed as a backup in the event of radar failure. This technique was developed by DM4/M. Veres and DM4/D. Mosel, with attitude calculations by J. Holloway and D. Edwards. The theory behind this technique is as follows:

Since the positions of the flux tubes in relation to the PDP in the LVLH reference frame are known, it is possible to define an attitude which would point the -Z axis of the Orbiter at the PDP, if the Orbiter were at that given point. This attitude is achieved by specifying a variable body vector which, if pointed at the center of the Earth at the desired time, would result in the -Z axis of the Orbiter pointing at the PDP, provided the crew accomplishes transition inputs as required to place and maintain the PDP at the desired place in the COAS.

4. A unique FDF format was developed which conveniently and totally integrates the AUTO/NAV targeting procedures, the manual procedures, and the science operations. This was done because it was necessary to account for the possibility of the radar's failing at an arbitrary time during the PROX OPS, and because the science activities would take place concurrently with the PROX OPS. The timeline pages of the PROX OPS book contained the PROX OPS procedures in the usual two columns, but a third, central column was added to show summary level science procedure callouts for the mission and payload specialists. The facing pages contained AUTO targeting and NAV data, MNVR solution pads, and some contingency AUTO targeting data, along with the CDR's manual procedures. Manual targeting data for the PLT and MSI were contained in tables at the end of each section and on a cue card.
5. Due to the difficulty and time involved in generating orbit targeting I-loads, and performing attitude calculations for the manual technique and the vast amount of data which would have to be uplinked, it was decided to include several detailed contingency timelines in the book. These included options for delaying the start of PROX OPS by one or two REV's, and deleting the third REV of the flyaround, both with and without performing the final wake transits. Additionally, the entire set of procedures was repeated

for use on flight day 6 (FD3 was nominal) in the event that the PROX OPS could not be performed on the nominal day. Finally, a set of "generic" contingency procedures were included that were applicable on either day.

CREW TRAINING

1. Crew training was as big a challenge as any other area of preparation for the PROX OPS. Both techniques were simple in concept, but required much practice to perform at a high level of proficiency, which was necessary to conserve fuel. Both techniques required a high level of crew coordination and checklist discipline, which was achieved during the course of the training.
2. The AUTO/NAV targeting technique utilized the standard procedures of NAV, targeting, and burn execution which have been used on several previous RNDZ flights. However, it was much more intense in that there was, nominally, a total of 27 targeted burns and several complex manual MNVR's over a period of some 8.5 hours. In many cases, there were as little as 5 to 8 minutes between burns. This left little margin for error or time for discussion in the event of unforeseen problems. Also, in order to achieve the desired trajectory control, it was necessary to trim each burn to 0.1 ft/s, rather than the usual 0.2 ft/s. This was very difficult because of noise in the guidance system.
3. The manual targeting technique offered constant closed loop trajectory control, and was largely independent of radar failure or navigational errors. However, manual-targeting was a far more crew-intensive task than the AUTO technique, in that constant "out the window" attention and manual piloting corrections were required. Additionally, constant monitoring and adjustment of the attitude MNVR rate was necessary.
4. The most effective crew training from a PROX OPS standpoint occurred in the SES. This was due to the excellent quality of the visuals, the availability of correct orbit-targeting I-loads, the convenient reset points that were available about 1 year prior to launch, and the general flexibility of the facility and personnel.
5. Quite the opposite was true of the SMS. The PDP was difficult to see in the daytime at ranges greater than 400 to 500 feet (typical ranges were 600 to 1400 feet for most of the profile), and it was invisible at night or with the Earth in the background. The SMS instructors had to swap the PDP for a fake TGT and vary its brightness for day versus night passes. They generally did a good job of this, but there were times when no TGT was visible for several minutes. This was not a serious impact for the AUTO technique, but it rendered the SMS at best, useless, and at worst, counter productive for training in the manual technique.

6. Another serious SMS problem concerned the untimely delivery of proper I-loads. The crew had only one training session (an integrated sim) with the correct trajectory and I-loads, which occurred exactly 1 week prior to the scheduled launch. This is absolutely unacceptable! Since the crew had gotten used to changing nearly all of the TIG times for their targeted MNVR's because of improper SMS I-loads, negative training was actually accomplished. This assertion was proven in flight when it became necessary to change base time when we were at a lower orbital altitude because of the abort to orbit. The crew went on changing TIG's, rather than changing basetime, which slightly altered the trajectory. After much discussion within the MCC, and two or three calls to the crew, the proper procedure was finally implemented. This should never have happened, and would not have happened had the SMS been properly configured at an early date. Fortunately, the results were probably not serious.

CREW ORBITER SYSTEMS INTERFACE

a. CCTV Operations

The crew reported that the CCTV ranging charts worked well; however, the pan and tilt adjustments were easily misaligned after PRCS firings by as much as 5° to 10°. It is therefore recommended that the cameras be realigned just prior to starting the final approach to grapple.

The crew noted that the PDP, as seen in the CCTV, was a "blob that changed its shape." This problem was especially bad at night. When the Sun was in front of the PDP (from sunrise to noon), an image good enough to use the ranging rulers could be obtained, but only after much dedicated effort. The poor image made it difficult to detect small rates, which means that while the PROX OPS could still have been accomplished using the manual technique, it would have cost more fuel. This problem also contributed to the difficulty in establishing the precise stationkeeping position required to set up for the manual roll MNVR. The CDR commented that he finally resorted to using the radar angles for this task. The CDR also noted that while the CCTV image jumped during PRCS firings, the motion quickly damped out.

b. RR Operations and Alternate Ranging Devices

The range rate data provided by the radar was not quite as noisy as that in the SES radar model. However, it was so noisy that the CDR found it necessary to use either the navigated state or apply a "mental filter" to judge his range rate.

The inertial LOS rate needles were "a little jumpy," but still usable, if time was taken to watch them and apply a mental filter. Fine control was not possible, but they may be useful at long ranges. Other RNDZ crews have made similar comments. Their

usefulness may be a function of range and TGT size, radar reflectivity characteristics, and attitude rates. Consideration should be given to developing a procedure to use this information when possible.

MS2 made several attempts to determine range using the parallax rangefinder. The MS2's attempts resulted in a bias of about 10 percent long over ranges of 600 to 900 feet, as compared to the radar.

c. Beta Angle

The PROX OPS was performed while the beta angle was in the vicinity of $+20^\circ$. Due to the sequence of events, this was a factor only during the initial stationkeeping and during the descent to the V-BAR following the last wake transit end (WTE) MNVR. Both of these tasks were performed manually. The CDR felt that although there were times when he had to shield his eyes from the Sun, a 20° beta angle was not a problem, and a "somewhat smaller" angle would have been acceptable.

In the event of a smaller beta angle, the CDR was confident that he could have "flown on instruments," provided that the radar was working. In fact, that method was used to establish the initial V-BAR stationkeeping. This method seems to be the best in situations where precise control of positions and/or rates is required.

d. Orbit Targeting

Although a detailed analysis of targeting and guidance performance is beyond the scope of this report, a few general remarks are in order.

- All onboard burn solutions were well within precomputed limits.
- As expected, it was very difficult to trim the burns to within 0.1 ft/s. This was especially true with MNVR's having short (5 min) transfer times. There appears to be a tradeoff between using short transfer times (which minimizes the propagation of trim errors) and the more accurate trimming possible with longer transfer times. In the latter case, the original trim error to be propagated would be smaller. It may also be possible to alter the VGO corrector task in Lambert guidance such that it would result in less noise in the VGO's presented to the crew.

The large trajectory dispersion following the W3S burn is as yet unexplained, since the crew successfully performed that burn, and the residuals were small. An option to be explored is whether it would have been better to perform the wake transit start and end burns based on elevation angle, rather than time.

e. Flight Data File (FDF)

The crew commented that while informal communication and advice were valuable, the FDF should incorporate as much information of this nature as possible. In other words, "the FDF is the last word," and all last-minute changes should be included.

The only serious deficiency of the PROX OPS book in this regard, of which I am aware, concerns the post-phantom-point midcourse maneuver. It was discovered that trajectory dispersions due to trim errors performing a midcourse about 10 minutes after the PH burn, improved the lower flux tube accuracy. Discussions with the crew and flight director resulted in the decision that the post-PH midcourse would be executed per a real-time call based on an evaluation of PH burn residuals. Although all interested parties understood this agreement, and it worked smoothly in real time, a procedure for performing the targeting and execution of the midcourse should have been included in the PROX OPS book, preceded by an "if required" statement, much like what was done with the second TDRS data dump. However, it should be noted that a tele-printer message was transmitted which contained TIG times and TGT set numbers for the midcourses. Also, the crew commented that they were pleased with the book, and that "if we had to do it again, we wouldn't change a thing."

The CDR commented that it would have been handy to have translation pulse sizes, and perhaps attitude DB data on the "Execute RCS Burn" cue card. This probably comes under the heading of a "crew preference item," but the format would be useful, particularly for missions of this nature. This option should be made available for each crew.

SUMMARY

In summary, several key points merit emphasis.

1. The flux tube connections and wake transits were accomplished with sufficient accuracy to obtain good scientific data.
2. The amount of propellant used was acceptable.
3. A postflight examination of the crew's PROX OPS books used in flight revealed meticulous attention to detail, exemplary checklist discipline, and good crew coordination. These factors were chief contributors to a successful mission.
4. Procedures development was a long, arduous process, spanning some 2 years. Many avenues were explored during the early phases, resulting not only in good procedures and a successful flight, but in a greater understanding of the capabilities of the current system, and new ideas concerning how it might be improved. Some of those ideas have already been incorporated. One of the republished

contingency procedures (the REV 3 waveoff) was a key to mission success following the abort to orbit.

5. It is clear that the SES is the best place to conduct training for RNDZ and PROX OPS missions; and that DM4 personnel should support all related phases of the crew's training.
 6. No adequate backup for the radar has yet been found. All alternate ranging devices tested to date have been found to have limitations in useful range, accuracy, or both. The Ku-system has had problems in flight. We are fortunate that radar failures have not occurred during a RNDZ or PROX OPS mission.
- I. STS 51-I was launched Aug 27, 1985/1058 GMT, with a crew of Engle (CDR), Covey (PLT), Van Hoften (MS1), Lounge (MS2), and Fisher, W. (MS3). After deploying a commercial payload, the crew performed a RNDZ with the Syncom, which had broken on STS 51-D, and repaired it.

The rendezvous profile is shown in figure A-11. Specific features unique to this mission include elliptical orbit, stable relative position post-NSR, and preplanned in-close flyaround.

The "Rendezvous FDO" (Brian Jones) produced the following account of mission maneuvers:

- Three deployables, one RNDZ. Syncom was in an elliptical orbit (160 by 235).
- Orbiter was inserted into a 190 n. mi. circular orbit for the deploys. Phasing (variable orbit) was not allowed until all three deployables were out of the bay. This was a premission constraint imposed because of the late manifest change. Both PAM's required at least a 190 n. mi. circular orbit because they were using the heavy, beefed-up nozzles and without them, their insurance rates would go up a great deal.

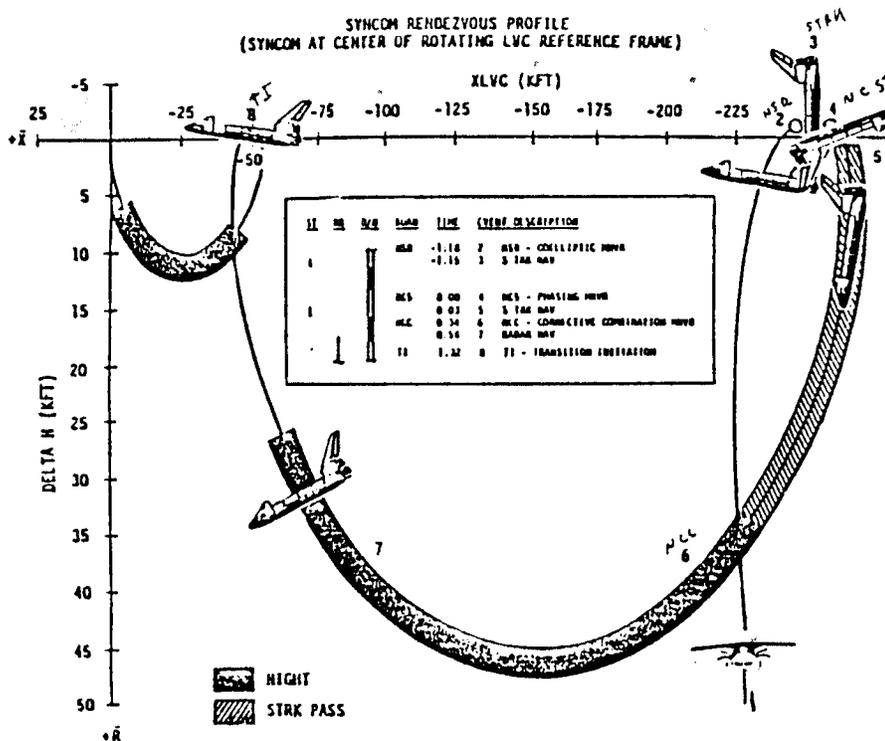


Figure A-11.- Rendezvous profile, STS 51-I.

- NC1 TIG selected to fix the line of apsides.
- NC2, NC3, NC4, and NH2 were planned for 0 ft/s (i.e., no posigrade bias) to yield to maximum launch window. This also allowed them to be deleted in real time without any effect on the profile.
- NSR was placed as late in the profile as possible (between NH and NC5) to yield the maximum launch window. NSR was required to set terminal phase lighting.
- Because of the NSR placement, this was a one-ST pass RNDZ. The profile is more sensitive to dispersions at Ti as a result.
- Typical one REV transfer to Ti because of the EVA requirement (crew workday).
- The following postflight report was prepared by the Rendezvous Procedures office (DM43).

TABLE A-6.- 51-I NAVIGATION PERFORMANCE

<u>Event</u>	<u>Star TRK 0</u>	<u>Star TRK 1</u>	<u>RR Pre-TI</u>	<u>RR Post-TI</u>
Lock on range	303,802 ft (50 n. mi.)	333,072 ft (54.8 n. mi.)	146,935 ft (24.2 n. mi.)	54,500 ft (9.0 n. mi.)
Lose lock range	304,429 ft (50.1 n. mi.)	LOS	48,000 ft (7.9 n. mi.)	-85 ft
1st SV update	186 ft	814 ft	103 ft	58 ft
Last SV update	13 ft	530 ft	0 ft	LOS
Range marks	N/A	N/A	163	772
R-DOT marks	N/A	N/A	162	772
Angles marks	23	158	161	697
Time	~3 min	~19 min	~22 min	~138 min

The first STRK pass, though short, was very good. The first SV update was 186 feet, indicating that the ground tracking was good. The last update was 13 feet which indicated that the SV was well on the way to being converged. Even though only 23 marks were processed, the results were excellent. A good first STRK pass is protection against subsequent STRK failure.

The second STRK pass was also a good pass. The first SV update was 814 feet while the last update was 530 feet, occurring after 158 marks. This pass lasted approximately 19 minutes and provided the majority of the STRK NAV with the best viewing geometry for this flight.

The radar first detected the Syncom at 27.8 n. mi. This was a momentary detection with full radar lock-on not occurring until 24.2 n. mi. The last radar marks used for Ti targeting were taken into NAV 7.9 n. mi. The first SV update was 103 ft and the last update, prior to going to OPS 202, was a 0-foot update. Since the Ti burn was a left OMS burn, the radar did not drop lock during the maneuver to burn attitude during the burn, nor during the return to -Z axis TGT track. However, when OPS 202 is entered prior to Ti, the input from the radar is no longer processed by the NAV software. Range and range rate mark processing resumed as soon as the crew returned to OPS 201. The post-Ti lock-on range represents the point at which the radar angle marks were re-enabled and full NAV processing resumed.

The dispersions at Ti were 1458 feet long and 365 feet high from the targeted position. This resulted in an MC2 TIG slip of 1 min 23. The out-of-plane null for this flight was 0.13 ft/s.

TABLE A-7.- 51-I PROPELLANT USAGE

Propellant Usage (LB)

<u>Eveny</u>	<u>Forward</u>	<u>Aft</u>	<u>I/C</u>	<u>OMS</u>	<u>Total</u>
NSR burn	26	9	30	1008	1073
NC5 burn	26	0	49	464	539
Ti burn	22	0	25	493	540
MC 1	-	-	-	N/A	25
OOPN	-	-	-	N/A	28
MC 2	7	0	12	N/A	19
MC 3	4	0	18	N/A	22
MC 4	9	0	14	N/A	23
Manual phase	84	0	183	N/A	267
V-BAR approach to low Z	26	0	0	N/A	26
Low Z to sunset	70	0	130	N/A	200
Sunset to no low Z (night)	124	0	76	N/A	200
Total V-BAR app. to no low Z	220	0	206	N/A	426
SK to sunrise (31 min)	0	0	83	N/A	83 (2.68 lb/min)
Period of rate matching	397	0	436	N/A	833

The propellant usage during the RNDZ portion of the flight (beginning of the RNDZ book to the V-BAR arrival at the end of the manual phase) was within predictions. The NSR burn was a large burn (total ΔV 48 ft/s) while the NC5 and Ti burns were both less than half that size. All the midcourse burns were of the same magnitude and roughly equal in prop cost. Manual phase (2 minutes post-MC4 to stable on the V-BAR) cost a total of 267 lb which was only 38 lb above the predicted mean and well within 1 sigma.

During the V-BAR approach, the prop usage was nominal. However, when the flight entered the PROX OPS phase, the propellant usage deviated tremendously above the predicted. When it came time to leave low Z mode, the crew punched the low Z pbi, but because of sunshafting coming in through the overhead windows, they could not read whether the pbi

light was on or off -- off being the no-low Z mode indication (i.e., NORM Z). Since they were not sure that they had left low Z mode, they pressed the low Z pbi again. During this time, they were LOS and the MCC could not offer any insight. Postflight data shows that the initial depression of the low Z pbi did take the Orbiter out of low Z mode and that the second depression returned the vehicle to low Z mode. The crew, believing incorrectly that they were now in NORM Z, subsequently performed the final braking and establishment of 35-foot stationkeeping in low Z mode as opposed to norm Z mode as called for by the procedures. This cost 400 lb of propellant rather than the expected 40 to 50 lb.

After stabilization at the 35-foot stationkeeping position, the crew recognized that the low Z mode was still enabled and disabled it. At this point, all attention was focused on the two EVA crewmembers as they struggled to get the capture and grapple bars out of their carrier. The Syncom was tucked lower than 35 feet in the bay for better lighting at night, and it was slowly drifting aft. When the crew realized that the Syncom was too far aft, near the tail, the view of the TGT out the aft windows (vice the former view out the overhead windows) caused temporary confusion between aft sense of -Z (normally, facing "up") and -X (normally, facing "aft"), and improper THC inputs were executed ("sense" had always been "-Z", but several THC inputs were made as if "sense" were "-X"). The TGT was already over the OMS pod and it was inadvertently plumed. This induced unplanned rates on the Syncom which turned out to be difficult to match. In an attempt to match Syncom rates with Orbiter rates, the crew began a period of approximately 30 minutes where postflight data shows Orbiter rates greater than 0.2 deg/s and at times exceeding 0.8 to 1.0 deg/s. The propellant usage during this period of attempted rate matching totaled 833 lb. Completely matching the Syncom rates turned out to be unsuccessful. Astronaut James Van Hoften finally acted as a "flexible end effector" and wrestled the last remaining rates out of Syncom.

LESSONS LEARNED

The lessons learned from the flight have impacts on flight design, procedures, and training. The flight design considerations involve the planning for STRK passes. Upon examination of dispersion data, we found that the lack of the first STRK pass leads to greater dispersions at Ti with subsequent dispersions at V-BAR arrival. If the radar is working for the terminal phase, this represents no problem. However, there could be major impacts to a radar-failed terminal phase. The three sigma dispersion cases could require more propellant than is currently budgeted and put mission success into jeopardy. The flight designers need to provide as much time as possible for the first STRK pass with the goal of providing two full STRK passes prior to Ti. Procedurally and during flight, every opportunity must be given the crew to maximize the STST data during the STRK passes.

A lesson learned from the integrated sims involves the NAV management immediately post-Ti. Post-Ti we nominally go back to use the RR. If

TABLE A-8.- 51-I MNVR SUMMARY

MNVR	TIG	ΔV	VX	VY	VZ	Ha	Hp
MPS DUMP	0/00:09:35	10.0	9.6	0	-2.7	191	-
OMS-2	0/00:40:21	278.6	276.4	15.7	31.2	191	190
AUSSAT SEP	0/06:50:14	11.2	10.7	0.1	-3.2	196	190
ASC SEP	0/11:24:32	11.1	10.6	0.1	-3.2	202	190
SYNCOM F4 SEP	2/00:05:54	15.2	14.6	-0.1	-4.3	211	190
NC1	2/06:12:42	2.7	2.7	-0.1	-0.1	212	191
NH1	2/06:58:28	35.7	-35.7	0.1	-0.8	212	170
NPC	3/05:34:21	8.8	0.1	8.8	0.2	212	170
NC2	3/06:39:07	0.9	-0.9	0.1	0.1	212	170
NSR	3/20:24:15	47.7	47.7	-0.1	-0.9	239	170
NC5	3/21:38:56	17.7	-17.7	0.1	0.3	233	166
NCC	3/22:12:55	1.3	-0.7	0.0	1.1	233	166
TI	3/23:10:55	13.5	13.5	0.6	1.4	238	169
MC1	3/23:33:37	0.6	-0.1	0	0.6	238	169
PLANE NULL	3/23:46:44	0.2	0.0	0.2	0.0	238	169
MC2	4/00:01:30	0.4	-0.3	0.0	0.3	238	169
MC3	4/00:11:30	0.4	-0.3	0.0	0.3	238	169
MC4	4/00:21:30	0.3	0.2	0.1	-0.2	238	169
VBAR	4/00:49:15	-	-	-	-	239	170
SYNCOM F3 SEP1	5/04:30:30	2.1	0.0	2.1	0.0	239	170
SYNCOM F3 SEP2	5/04:45:30	3.1	3.0	0.0	0.1	241	170
ORBIT ADJUST	5/22:20:00	15.2	15.2	-0.2	0.0	242	178
DEORBIT	7/01:13:00	475.6	-364.5	0.0	-305.3	184	-

the radar has a problem and it is not giving valid NAV data, crews need to go immediately to the STRK and take STRK angles. Once this angle data is assured, then they can return and attempt to troubleshoot the radar. During the sims, we spent too much time trying to troubleshoot the radar prior to going to the STRK. The result was a shortened STRK pass which yields poorer NAV data.

The crew also had problems during the off-nominal PROX OPS after the Syncom was plumed. Part of this problem was discovered during a crew debriefing. Since the Syncom was held lower than 35 feet (approximately 25 feet), the CDR could see the satellite out the aft window. He mentally changed his reference frame for the THC from -Z to -X. The Orbiter sense switch, however, was not physically changed. This exacerbated the aft movement of the Syncom and contributed to its being plumed. While trying to match rates, the crew also put the Orbiter into pulse mode in pitch and yaw. This was not called for in the nominal procedures and was not examined as a contingency. This configuration is propellant inefficient.

- J. STS 61-B was launched November 27, 1985/0029 GMT, with a crew of Shaw (CDR), O'Connor (PLT), Ross (MS1), Cleave (MS2), Spring (MS3), Walker, C. (PS1), and Neri (PS2). Several commercial PL's were deployed and two EVA's were performed for space construction tests. A TGT was manually deployed for new PROX OPS techniques testing involving the OEX DAP.

The purpose of this flight test was to expand the knowledge gained from OEX DAP tests performed on STS 51-G. The OEX DAP was developed by the Charles Stark Draper Laboratory with potential application to the present Orbiter or future space vehicles. The most rigorous test associated with the STS 61-B activity was known as "real target stationkeeping," for the purpose of evaluating the interaction of the closed loop RR and navigation system with the DAP. The target, consisting of two 15-inch diameter aluminum disks interlocked together to form a "sphere-like" object, was deployed by an EVA crewman following completion of a scheduled EVA. It was equipped with highly reflective tape which allowed nighttime visibility out to a maximum of 500 feet with the Orbiter overhead light, as determined by tests at Ellington Field.

The final version of the test plan (as documented in the STS 61-B PROX OPS book) called for a brief period of 35-foot stationkeeping to qualitatively evaluate the DAP manual handling qualities. An initial separation to 300 feet on the +V-BAR was performed, where, after manually establishing stationkeeping, the DAP was to be placed in the "position pulse" (POS PLS) mode to automatically stationkeep within a predefined position sphere, using the low Z mode. After 30 min, low Z was to be exited, and the POS PLS mode used to command an automatic translation to 400 feet on the +V-BAR, where another 30 min of SK was to be performed, this time in NORM Z. The Orbiter next was to automatically translate 100 feet below this point on the +V-BAR for a final 30 min of NORM Z SK, followed by a posigrade final sep MNVR and deactivation of the OEX DAP.

Unfortunately, a last-minute decision was made to leave the Ku-band system off the vehicle, due to KSC Orbiter processing flow schedule constraints. Therefore, only limited flight test data was obtained about the OEX DAP manual handling qualities. The crew performed 10 minutes of SK with the conventional DAP, then activated the OEX DAP. Of the approximately 1 hour of OEX SK, about 15 min were spent in "quiescent stationkeeping", with propellant usage comparable with preflight predictions. The remaining 45 min was used to perform a "tracking task," consisting of a series of small manual translation maneuvers to evaluate the OEX DAP manual handling characteristics. Qualitatively, the OEX DAP manual handling characteristics were found to be generally satisfactory.

Because of the in-flight absence of the Ku-band system, the preflight procedures development/validation work done in the SMS (coupled with the comparison runs done in the SES) may well constitute the most thorough and meaningful evaluation of the automatic PROX OPS features of the OEX DAP. One of the most important results of that process is that while the difference in propellant usage between the two DAP's was statistically indistinguishable (perhaps partially due to the small number of runs available), the OEX DAP did not demonstrate a capability to duplicate the precision which a human pilot can achieve in flying the PROX OPS. This is not necessarily bad, since there may be future requirements to remain close to another vehicle for long periods of time, but precise SK is not necessary to perform that task.

The limited amount of procedures development time did not allow sufficient experimentation in varying OEX DAP setup values. The SMS was the only JSC facility with the OEX DAP software, and only 16 hours of useful, dedicated procedures development time were obtained. If more procedures development time had been available in the SMS, experimentation might possibly have resulted in greater precision with acceptable propellant usage.

Another fringe benefit of these studies was the development of the capability to perform off-V-BAR SK. In this case, SK was performed 100 feet below a point 400 feet along the +V-BAR. Although not tested on orbit, this activity was satisfactorily accomplished in the SES, with fuel usage comparable to more conventional SK locations. However, it was a more crew-intensive task, because off-V-BAR locations are inherently unstable. Therefore, one would not expect to perform this type of activity for extended periods of time. SES work was done at ranges of 300 feet and 400 feet on the +V-BAR, both 100 feet above and 100 feet below. A position below the V-BAR is preferred because visual cues with the COAS are better, and the propellant usage is almost exclusively from the aft system.

In conclusion, the OEX DAP was shown to have many features which would be highly desirable to have on the Orbiter. Some of them may be mandatory for unmanned vehicles which will operate in an autonomous mode. Unfortunately, there was not enough time between the final

decision authorizing the "real target stationkeeping" tests on STS 61-B and the launch to develop a rigorous test plan in an optimum manner and to smoothly integrate it into the overall mission planning process. The loss of the Ku-band system just 3 weeks prior to launch made it impossible to accomplish any of the major preplanned PROX OPS test objectives; the whole operation was on such a "success-oriented" schedule that it was not possible to develop a worthwhile "no-radar" test plan while struggling to develop the nominal test plan. Therefore, further testing is required before any of these capabilities can be implemented.

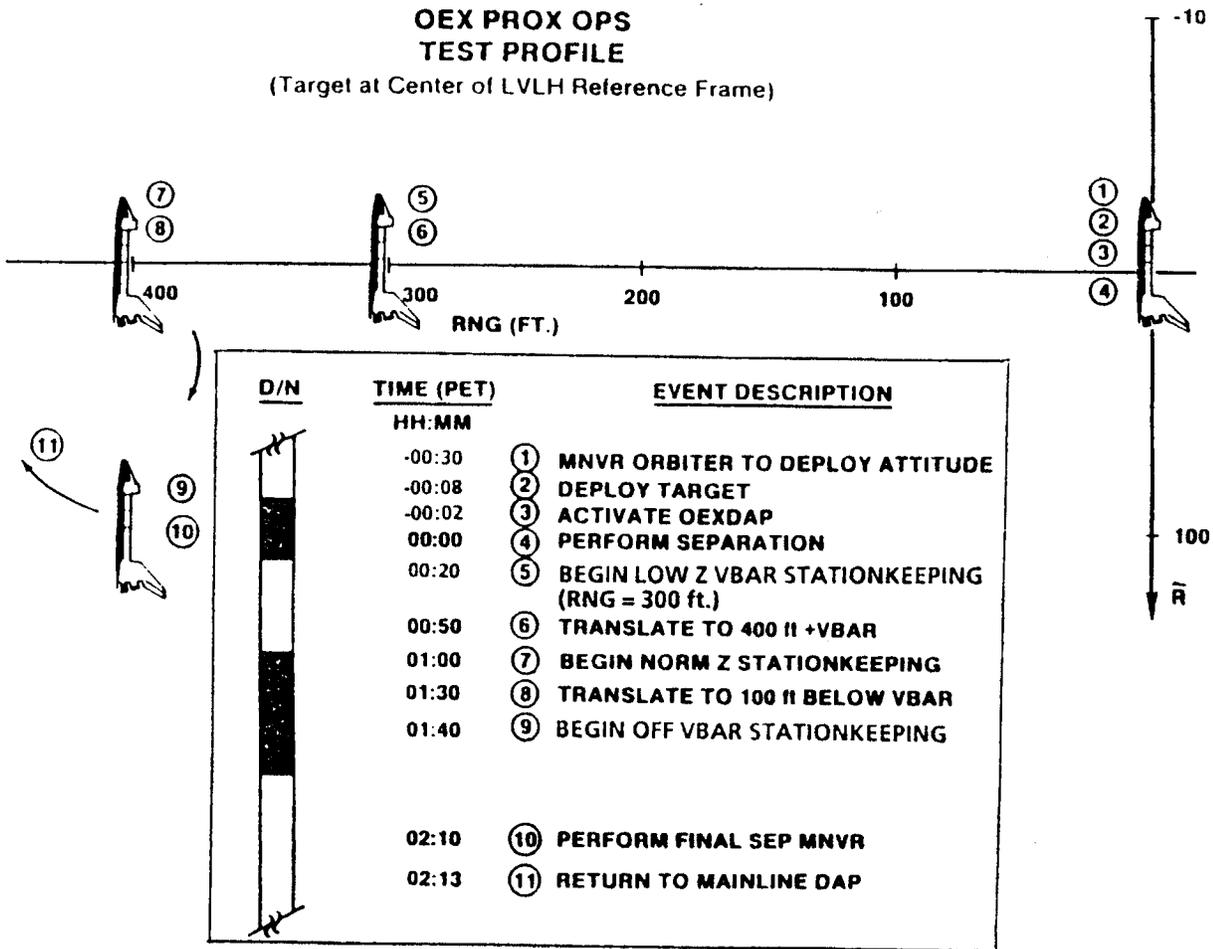


Figure A-12.- OEX DAP profile.

K. STS 51-L was lost during launch phase on January 28, 1986, along with the crew of Scobee (CDR), Smith (PLT), Onizuka (MS1), Resnik (MS2), McNair (MS3), Jarvis (PS1), and McAuliffe (teacher-in-space). One mission objective was to have been deployment and retrieval of the Spartan-Halley free-flier. The planned rendezvous profile is shown in figure A-13.

- This was a typical deploy and retrieve RNDZ.
- The separation MNVR is a canned MNVR executed on lighting. This eliminates the need for an NSR to fix the lighting or a propellant penalty to fix the lighting.
- NC1 phases the Orbiter to the NC2 location (typically 40 n. mi.).
- NH after to NC2 is normally too small to execute. NH is then targeted at the NCC point; the total ΔV cost will be smaller if you TGT NC2 this way.
- There is then a two-REV transfer to Ti. Typically, this kind of profile will be used if there is not an EVA requirement.
- The future flight generic Contingency Rendezvous book and Orbiter FSW are to be I-loaded for this type of RNDZ.

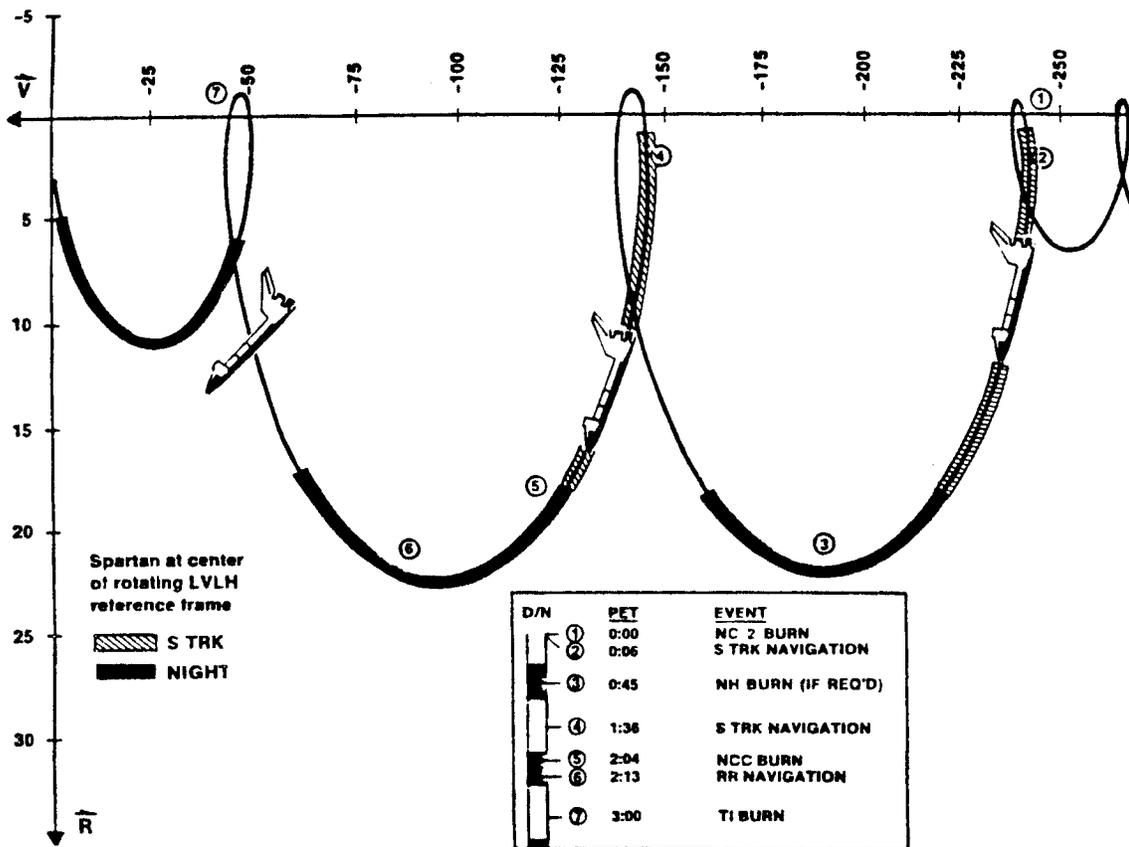


Figure A-13.- Rendezvous profile, STS 51-L.