

WORLD SPACEFLIGHT NEWS SPECIAL REPORT:

NAVIGATION WORKBOOK

SECTION 1

INTRODUCTION

NAV 2102

Advanced Training Series

**For Training Purposes only
Training Division
Flight Training Branch**

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The basic function of the Orbiter navigation system is to maintain an accurate estimate of the inertial position and velocity of the vehicle (called its state vector) with respect to time. In addition, during a rendezvous mission, the navigation system also must maintain an estimate of a target vehicle's position and velocity. This information is then used by the on-board guidance system in computing the commands required to transfer the vehicle from one position and velocity to another and to point the vehicle at a specified target (Earth, Sun, another orbiting vehicle, etc.). It is also used by the ground controllers for monitoring the health of the on-board navigation system. Additionally, information about the Orbiter and target state vectors is displayed to the crew on the dedicated displays and GNC CRT displays.

This workbook will cover the commonly used terms and functions associated with the navigation system. In addition, the ground and crew monitoring techniques and procedures available to maintain the health of the on-board state vector will be discussed.

SECTION 2
COORDINATE SYSTEMS

The position and velocity of the Shuttle must be uniquely defined in terms of an inertial coordinate system - a reference frame which is neither rotating or accelerating. This ensures that the normal equations of motion are valid. The on-board navigation system uses the M50 (Mean of 1950) inertial system defined in section 2.2. However, some quantities are much easier to define and some computations are considerably simpler if done in other coordinate systems. For example, when landing the Shuttle, it is more meaningful to give the position of the Shuttle relative to the runway than it is to give its position in a coordinate system fixed in space with its origin at the center of the Earth. Thus, the on-board navigation system uses a number of different coordinate systems to simplify the various inputs, outputs, and computations required. These inputs and outputs can then be expressed in any coordinate system by using coordinate transformations which are resident in the navigation software.

This workbook will not attempt to discuss the coordinate transformations or all of the coordinate systems used by the navigation software. However, a few coordinate systems do need to be understood, because they appear to the crew on certain dedicated displays and CRT displays. Also, they may be used to clarify certain aspects of navigation which will be discussed later.

All of the coordinate systems used are right-handed Cartesian systems. A right-handed Cartesian system has three mutually perpendicular axes, sequentially ordered such that each axis satisfies the application of the right-hand rule to the other two axes (XYZ system - apply right-hand rule to X-Y gives Z, to Y-Z gives X, to Z-X gives Y).

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2.1 BODY AXIS COORDINATE SYSTEM

This coordinate system has its origin at the Orbiter's center of mass and is oriented such that:

- Its X axis is parallel to the X_0 axis of the Orbiter structural body (Orbiter + External Tanks (ET) + Solid Rocket Boosters (SRB)). The X_0 axis is in the Orbiter plane of symmetry, 400 inches below the payload bay centerline; positive is toward the nose
- Its Z axis is parallel to the Orbiter plane of symmetry and is perpendicular to the X axis; positive is down with respect to the Orbiter fuselage
- Its Y axis completes the right-handed orthogonal system.

Note that vehicle pitch is rotation about the Y body axis, roll is rotation about the X body axis, and yaw is rotation about the Z body axis.

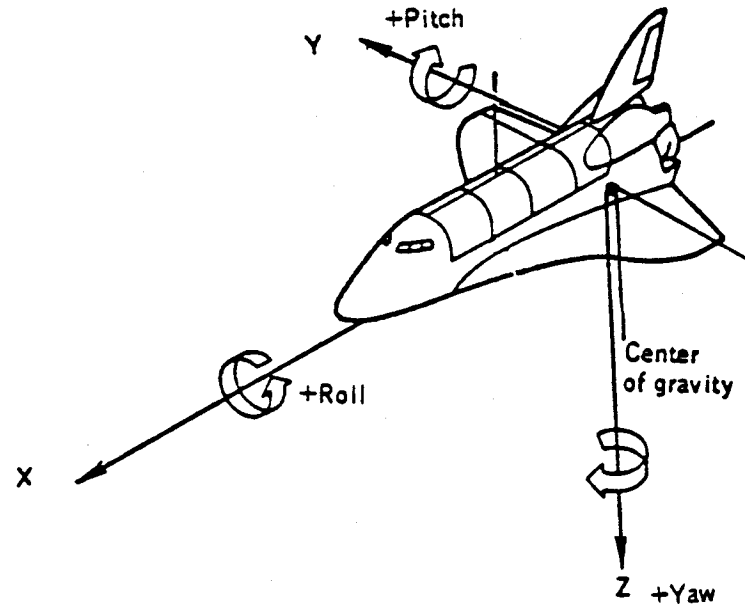


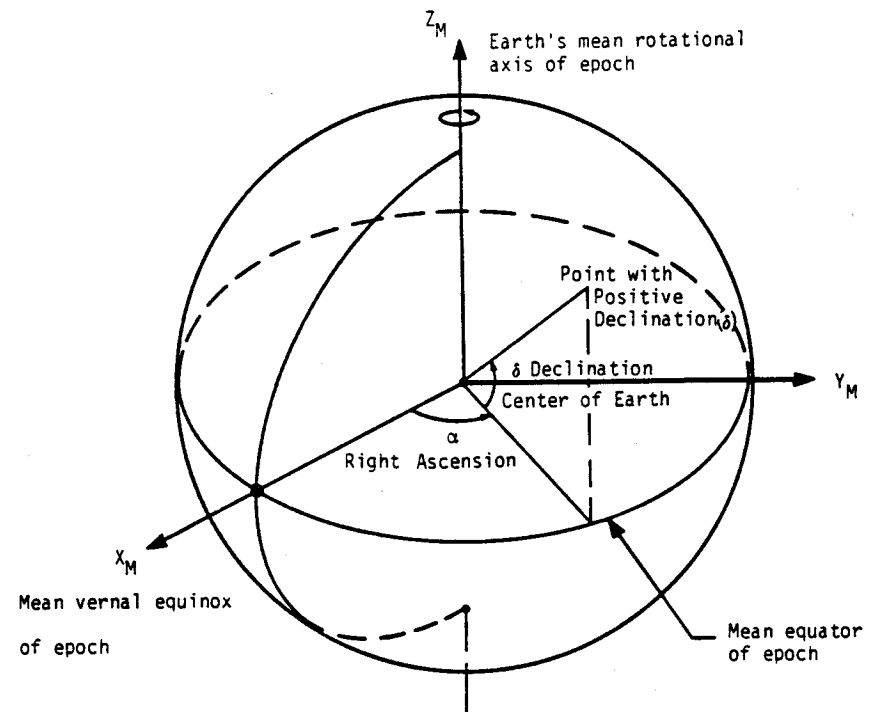
Figure 2-1. Body Axis Coordinate System

2.2 MEAN OF 1950 (M50) COORDINATE SYSTEM

The inertial coordinate system used by the on-board navigation system is the Aries Mean of 1950 Cartesian coordinate system, which generally is called the M50 system (figure 2-2). This system is used to establish and maintain the inertial position and velocity of the Shuttle during all phases of flight. The X-axis points towards the mean vernal equinox (apparent point on the celestial sphere where the sun crosses the Earth's equator on its northward journey) of 1950, the Z-axis is along the Earth's mean rotational axis of 1950, and the y-axis completes the right-handed system. It is important to understand that this is an inertial system and, although its origin is at the Earth's center, it is completely independent of the Earth's rotation.

Although the M50 system uses Earth orientations for the year 1950, it differs less than 1° from the analogous true-of-date system. The on-board system corrects for this difference, so that one can say that the inertial X-axis points to the current vernal equinox, the inertial Z-axis is along the current Earth rotation axis, and the inertial X-Y plane is the current equatorial plane.

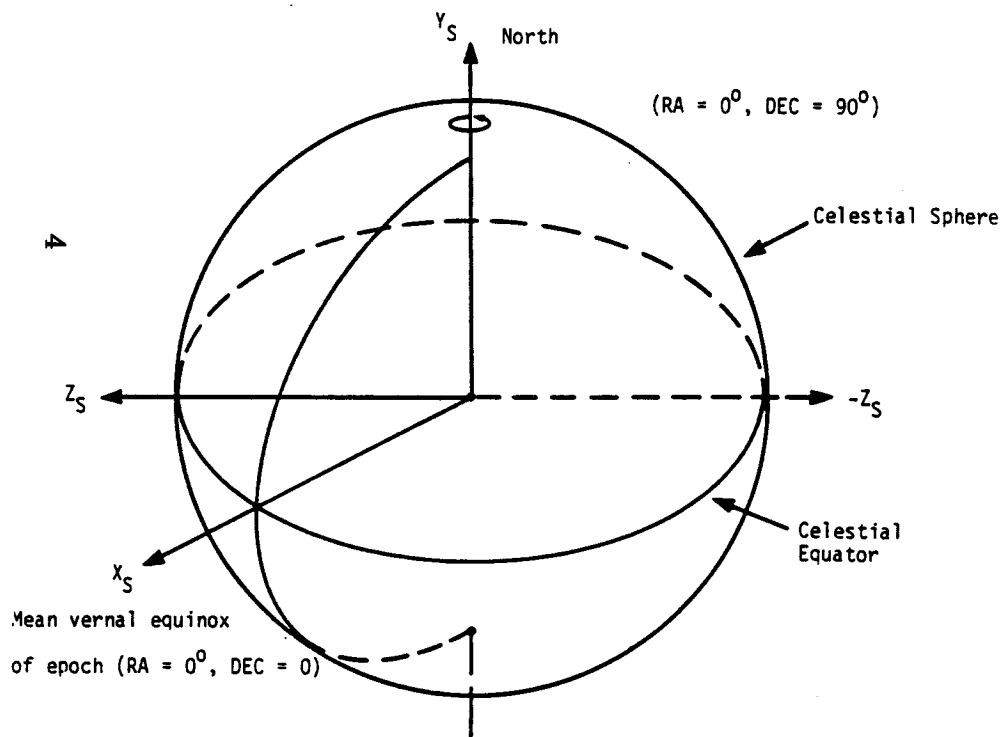
The crew can see Orbiter attitude and acceleration data with respect to the M50 coordinate system on the IMU ALIGN display (SPEC 21) in OPS 2 and 3. For other display purposes, such as the Attitude Display Indicator (ADI) and the UNIV PTG display, the vehicle's attitude is transformed into another coordinate system, called the STARBALL reference frame, which is a variation of the M50 coordinate system. See figure 2-3.



ω

NAME:	Aries Mean of 1950, Cartesian coordinate system
ORIGIN:	The center of the Earth
ORIENTATION:	The epoch is the beginning of Besselian Year 1950 The X_M - Y_M plane is the mean Earth's equator of epoch. The X_M axis is directed toward the mean vernal equinox of epoch. The Z_M axis is directed along the Earth's mean rotational axis of epoch and is positive north. The Y_M axis completes a right-handed system.
CHARACTERISTICS:	Inertial, right-handed Cartesian system.

Figure 2-2. Aries Mean of 1950, Coordinate System



2.3 EARTH-FIXED SYSTEMS

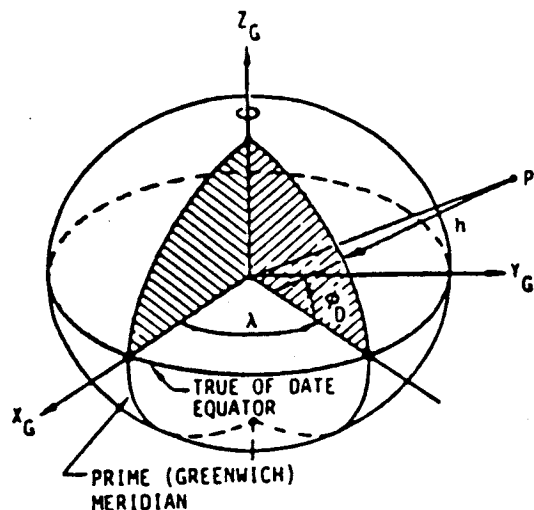
For launch, landing, and Earth observation one needs to know the Shuttle position and velocity in coordinate systems fixed to the Earth. These are non-inertial systems that are related to the M50 system by transformations that depend on time, Earth rotation rate, and the latitude and longitude of the point of interest.

2.3.1 Geodetic Coordinate System. One of the Earth-fixed coordinate systems uses the geodetic parameters defined in figure 2-4. This system uses an ellipsoidal model of the Earth called the Fischer ellipsoidal model. This model takes into account the shape of the Earth and thus gives improved detail over a spherical model of the Earth.

NAME: Starball reference frame
ORIGIN: Orbiter c.g.
ORIENTATION: +X_S axis points at 0° RA and 0° DEC on the celestial sphere
 +Y_S axis points at 0° RA and 90° DEC
 +Z_S axis points at 270° RA, 0° DEC
PITCH = RIGHT ASCENSION
YAW = DECLINATION

Figure 2-3. Starball Reference Frame

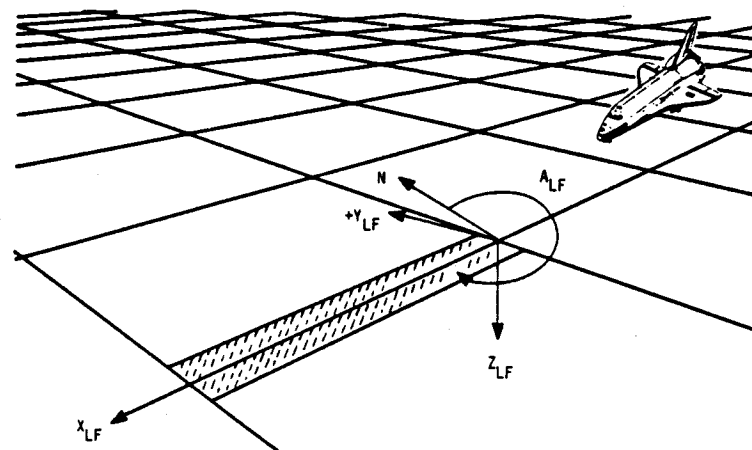
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- NAME:** Geodetic parameters
- ORIGIN:** This system consists of a set of parameters rather than a coordinate system; therefore, no origin is specified.
- ORIENTATION:** This system of parameters is based on an ellipsoidal model of the Earth (e.g., the Fischer ellipse of 1960). For any point of interest we define a line known as the geodetic local vertical, which is perpendicular to the ellipsoid and which contains the point of interest.
- h , geodetic altitude, is the distance from the point of interest to the reference ellipsoid, measured along the geodetic local vertical, and is positive for points outside the ellipsoid.
- λ , is the longitude measured in the plane of the Earth's true equator from the Prime (Greenwich) Meridian to the local meridian, measured positive eastward.
- ϕ_D is the geodetic latitude, measured in the plane of the local meridian from the Earth's true equator to the geodetic local vertical, measured positive north from the equator.
- CHARACTERISTICS:** Rotating polar coordinate parameters. Only position vectors are expressed in this coordinate system.

Figure 2-4. Geodetic Coordinate System

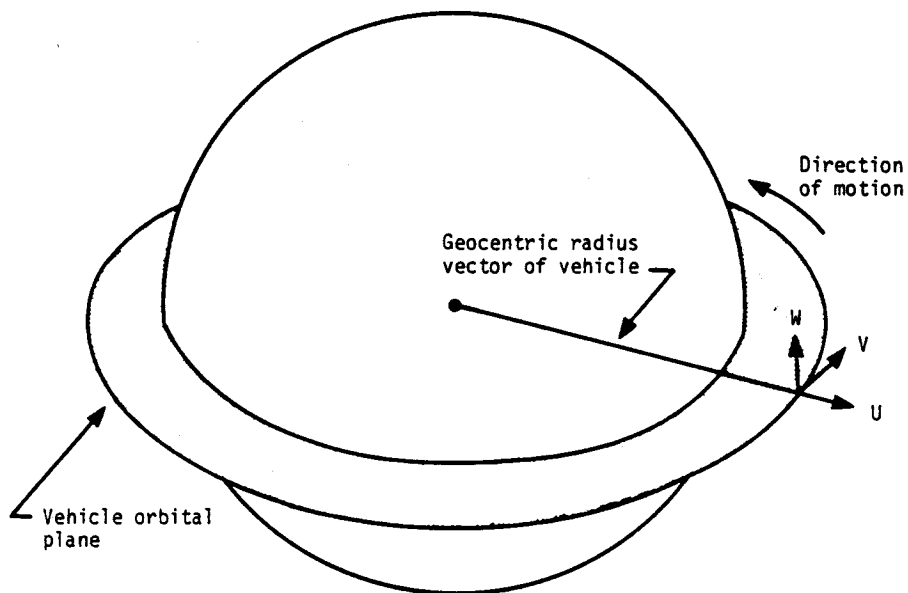
2.3.2 Runway Coordinate System. Another example of an Earth-fixed coordinate system is the runway coordinate system defined in figure 2-5. This system is used by navigation and the crew during ascent, entry, and landing phases of flight.



- NAME:** Runway coordinate system
- ORIGIN:** Runway center at approach threshold
- ORIENTATION AND DEFINITIONS:**
- z_{LF} axis is normal to the ellipsoid model through the runway centerline at the approach threshold and positive toward the center of the Earth.
- x_{LF} axis is perpendicular to the z_{LF} axis and lies in a plane containing the z_{LF} axis and the runway centerline (positive in the direction of landing).
- y_{LF} axis completes the right-handed system.
- A_{LF} is the runway azimuth measured in the $x_{LF}y_{LF}$ plane from true north to the $+x_{LF}$ axis (positive clockwise).
- CHARACTERISTICS:** Rotating, Earth-referenced

Figure 2-5. Runway Coordinate System

2.3.3 UVW Coordinate System. The final coordinate system to be discussed is the UVW system shown in figure 2-6. This is sometimes called the up-downrange-crossrange system since this is descriptive of the directions along which the axes lie.



SECTION 3
STATE VECTOR MANAGEMENT

The navigation system maintains its knowledge of the Orbiter's position and velocity with a group of six numbers (X, Y, Z, V_x, V_y, V_z) called the state vector. Associated with this state vector is a time tag. When rendezvous navigation is used, knowledge of the target vehicle's state vector must also be maintained. The navigation system uses the standard equations of motion along with the information it receives from the Inertial Measurement Units (IMU), the nav sensors (TACAN, ADTA, MLS, ST, RR, COAS), and the software models of the forces acting on the Orbiter (gravity, drag, vents, etc.) to predict the components of the state vector at each time value. This process is called state vector propagation. Inherent in this propagation scheme are errors. The equation of motion and the propagation technique are approximations, as are the gravity, drag, and vent models. In addition, the acceleration, position, and range rate information received from the IMU's and nav sensors are also imperfect. To correct these errors, which grow with time, the ground controllers periodically uplink a new state vector or a delta to the current on-board state based upon the more accurate ground radar tracking data.

The above subjects will be discussed in more detail in the ensuing paragraphs, as will the crew navigation monitoring tasks in each flight phase.

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- NAME: UVW coordinate system
- ORIGIN: Point of interest
- ORIENTATION: The U-V plane is the instantaneous orbit plane at epoch.
- The U axis lies along the geocentric radius vector to the vehicle and is positive radially outward (\approx altitude)
- The W axis lies along the instantaneous orbital angular momentum vector at epoch and is positive in the direction of the angular momentum vector (\approx crossrange)
- The V axis completes a right-handed system ($V = W \times U$) (\approx downrange)

Figure 2-6. UVW Coordinate System

3.1 FORCES ON THE VEHICLE

The state vector of the vehicle changes with time due to the forces acting on it. These forces include gravity, atmospheric drag and thrusting due to engine firings and vents. In order to maintain its knowledge of the state vector, navigation must maintain an estimate of each of the above forces. To do this, it receives inputs from the IMU accelerometers and from software models of gravity, drag, and vents. Note that an accelerometer cannot sense gravitational force because the accelerometer itself is being acted upon by gravity. Instead, it only can sense resistance to gravitational attraction. For example, an accelerometer placed on the ground would measure 1 g. This is the force of the ground on the accelerometer preventing it from falling. As another example, an accelerometer attached to an airplane senses the force of the air on the airplane (lift and drag). This is called drag force. Out of the atmosphere in coasting flight, an accelerometer reads ≈ 0 g's. Thus, accelerometers are used to sense non-gravitational forces. Gravitational forces must be computed using a model of gravity based upon the vehicle's position with respect to the Earth. The navigation software uses a multi-term series expansion model of gravity, each term of which adds to its accuracy, but also adds computational complexity. The first term of the expansion is called the central force term. This term is the expected gravitational force on the vehicle assuming the Earth is a perfect, uniform sphere. The next term is called the J2 term, which adds in the delta in gravitational attraction caused by the flattening of the Earth at the poles. It is on the order of 1000 times smaller than the central term. In the expansion, the third term is zero, so the next term of interest is the fourth order term which corrects for the pear-shaped Earth. This term is on the order of 10^6 times smaller than the first, central term (figure 3-1). The other terms of the series expansion are not modeled by navigation.

A second order, or J2, gravity model includes the central and J2 terms. A fourth order gravity model uses the central, J2, and fourth order terms. The value computed as the gravitational attraction on the vehicle is based upon navigation's estimate of vehicle position. Note that the magnitude of gravitational force on the vehicle changes less than 5% during a typical flight.

The other primary force on the vehicle is aerodynamic drag. Drag force varies widely during the ascent and entry phases and is small, though not negligible, on-orbit. Drag is a function of vehicle velocity, attitude, air density, and the vehicle's aerodynamic surface area. The IMU accelerometers are used to measure drag acceleration on the vehicle.

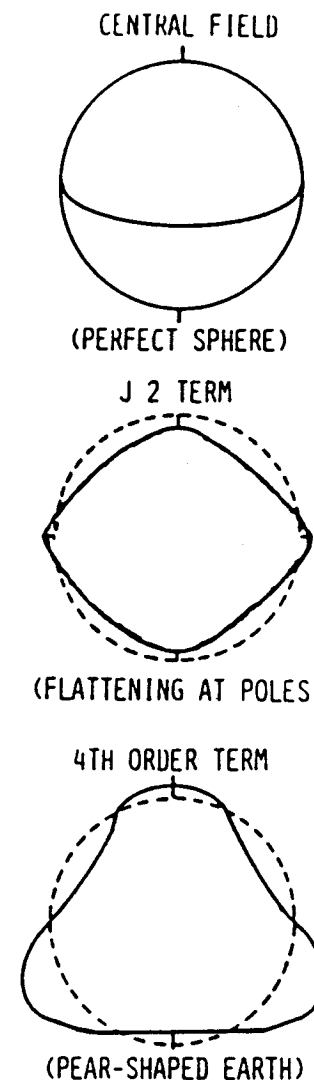


Figure 3-1. Gravitational Models Used by Navigation

IMU data is used only if it passes a threshold test, and in OPS 2 & 8, if navigation is placed in the mode in which it can use IMU data. This will be discussed in detail in Section 3.3

In cases in which IMU data is not used by navigation, a model of the vehicle's drag acceleration is used in the state vector propagation process. This model computes drag based upon the vehicle's nav-derived altitude (from which atmospheric density can be estimated), angle of attack, sideslip angle, and reference area. In OPS 2 and 8, the capability exists for the ground to uplink a factor to modify the computed drag in the case that the vehicle's reference area dramatically changes (such as if a large payload, a telescope for example, were exposed in the payload bay while still attached to the vehicle). This capability has not been required in the first STS flights.

If a vent, such as from the Auxiliary Power Units (APU) occurs, its magnitude may be under the IMU acceleration threshold. If such an event is expected in OPS 2 or 8, it is possible for the Mission Control Center (MCC) to uplink a magnitude, direction, start time and stop time for the vent which will then be used by navigation in state vector propagation. This capability, also, has not been used in the first STS flights.

3.2 SENSOR MEASUREMENTS

Navigation uses measurements from on-board sensors to improve its estimate of the state vector. In addition to IMU data (attitude and acceleration), navigation can use information from the TACAN, ADS, MLS, ST, COAS and RR systems. Also, it can use a model of the atmosphere to compute a pseudo-altitude measurement called drag altitude. As a review, the types of data and the most important features of each of the sensors will be covered in the following sections. More detail on each of these sensors can be found in the individual detailed workbooks.

3.2.1 Inertial Measurement Unit (IMU). There are three IMU's on the Orbiter located on a navigation base 55 feet ahead of the Orbiter center of gravity (c.g.). At a 6.25 Hz rate, the General Purpose Computers (GPC's) acquire attitude angles and sensed acceleration from each of the IMU's. Attitude data is derived from the measured IMU gimbal angles. Acceleration data is obtained from the two accelerometers in each IMU. Each accelerometer is a pendulous mass anchored to the IMU's case. An acceleration produces relative motion between the mass and the case. This motion is sensed and a voltage is applied to counteract it. The voltage required is proportional to the acceleration. This voltage is electronically converted to pulses which are accumulated. The accumulated pulses represent the changes in vehicle velocity during the time interval. Redundancy Management (RM) software takes the individual IMU attitude and accumulated ΔV data and uses it to form a single, more accurate value for vehicle attitude and acceleration.

In OPS 1, 2, 8, and 6, navigation propagates the state vector based upon the RM-computed acceleration value. In OPS 3, navigation propagates three state vectors, one based upon each IMU, and then chooses from the individual state vector components to form a "selected" state vector. The Backup Flight System (BFS) always uses the RM-selected acceleration value to propagate the state vector.

The accuracy of the IMU acceleration data is affected by errors in the alignment of the IMU. Thus, IMU data begins to degrade as the time from the last alignment increases because the IMU's drift with time. For this reason, an IMU alignment is required shortly before deorbit and every 2-10 hours during orbit.

3.2.2. Drag Altitude. During the "blackout" phase of entry (265K→160K ft. - the time frame in which no ground or external sensor inputs are available due to the ionization of the atmosphere caused by extreme heating), there is the potential that the nav state could begin to diverge. As it is critical that navigation be fairly accurate at the exit of blackout to preserve the Orbiter runway landing potential, navigation uses an atmospheric model of altitude versus air density to make corrections to the state vector. This computation of altitude is

called "drag altitude," because air density is calculated using the drag acceleration sensed by the IMU. The basic equation used is:

$$\begin{aligned} \text{Drag Force} &= \text{Mass} \cdot \text{Drag accel} \\ &= \frac{1}{2} \cdot \text{Air Density} \cdot \text{Velocity}^2 \cdot \text{Ref area} \cdot \text{Drag Coefficient} \\ \text{where Drag accel} &= \frac{\Delta V_{\text{IMU}}}{\Delta T} \\ \text{Mass} &= \text{Vehicle mass} \end{aligned}$$

Velocity = Derived from nav. state vector

Reference Area = aerodynamic area of the Orbiter (2690 ft²)

Drag Coefficient = function of angle of attack which is computed based upon IMU attitude data and the current velocity vector

Thus, given the current state vector, angle of attack, and IMU sensed ΔV (ΔV_{IMU}), air density can be computed. The software then uses its model of altitude versus air density (an atmosphere model) to compute the current altitude.

The accuracy of drag altitude is dependent, then, upon the accuracy of the IMU data and the atmospheric model.

6 Drag altitude becomes available during entry when the sensed drag acceleration reaches 11 ft/sec² ($\approx 240K$ ft for nominal end of mission) and can be used in navigation until air data is incorporated or altitude is less than 85K ft. The crew controls whether navigation uses drag altitude via an item on the HORIZ SIT display (HSD). This will be discussed in the section on the Kalman filter (3.4.1) and the section on entry nav sensor management (4.4.1). It is considered mandatory for drag altitude data to be used by navigation prior to exit from blackout.

3.2.3 Tactical Air Navigation (TACAN) System. Each of the three on-board Tactical Air Navigation (TACAN) units provide slant range and bearing to the TACAN ground station. TACAN redundancy management selects which of the TACAN data will actually be used by navigation. While the software provides for up to 10 TACAN ground stations to be available during entry, only two slots are used for any given landing site. The selection is set up so that one ground station is available in T/R and the other in GPC. Which ground station is used by a TACAN depends upon the TACAN channel selected via the TACAN CHANNEL thumbwheels on Panel 08 if T/R is selected on the TAC MODE switch (figure 3-2). For entry, if GPC is selected on the TAC MODE switch, the software automatically cycles through a specified subset of the TACAN stations assigned to the selected landing site until it establishes "lock-on". Each TACAN also has UPPER and LOWER antennas. Which of these should be used depends upon whether the Orbiter is banking away from or toward the ground station. The antenna controls are also on Panel 07. In the AUTO mode, the software determines which antenna is to be used. In the MANUAL mode, the crewmember can select the upper or lower antenna via the TAC ANT SEL SW. Each TACAN's channel, range and bearing measurements are displayed on the HORIZ SIT display (HSD). The range and bearing

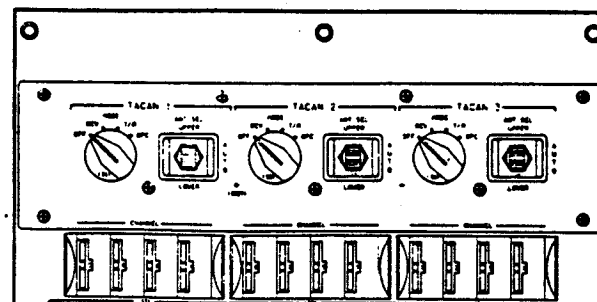


Figure 3-2. Panel 07 TACAN Switches

3041/050/		HORIZ SIT		005/01:50:00		000/00:20:00		
PT1	IMH2	ALTM					NAV DELTA	
INDEX		9 29.92					ΔX 10	
							CS ---	
							ΔY 11	
							CS	
							ΔZ 12	
							CS	
							ΔX 13	
							CS ---	
							ΔY 14	
							CS	
							ΔZ 15	
							CS	
							LOAD 16	
							18 ΔT 17	
NAV	RESID	RATIO	AUT	INH	FOR	TAC 111	TAC2111	TAC3111
TAC AZ	+2.2	0.0	19	20	21	+002.5	-002.0	+002.0
RNG	+1.0	0.1				+001.0	+002.0	+001.0
						DES 31	DES 32	DES 33
DRAG H	+100.0	0.0	22	23	24			
ADTA H			25	26	27	HWD37L		ABS 34
ADTA TO GNC			128	129	130	38R		DELTA 35

Figure 3-3. HSD TACAN DATA

appear as the absolute range and bearing to the ground station if ABSOLUTE is selected on the HSD or as the delta between the TACAN and NAV computed range and bearing to the ground station if DELTA is selected (figure 3-3).

Because of the horizontal directivity of the TACAN ground antenna radiation pattern, a volume of weak/poor radio frequency (RF) energy is created. The volume has the shape of an inverted cone whose included angle is 110° (see figure 3-4). This region is called the cone of confusion and, when in the cone, the TACAN bearing data will not be used by navigation.

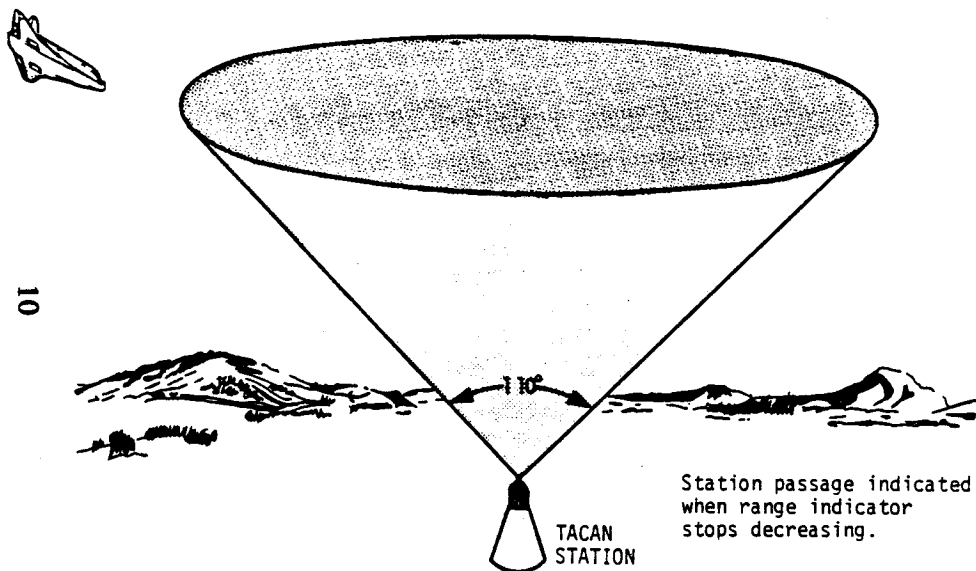


Figure 3-4. TACAN Cone of Confusion

In order for TACAN range data to be a candidate for use by navigation, it must be "locked on" for at least two TACAN's. Similarly, for TACAN-bearing data to be used by navigation, it must be locked on by two TACAN's. It should be noted that if range has not locked on, the antenna will cycle, which could make it impossible for bearing to remain locked-on. In cases in which only one TACAN has achieved lock and it is necessary to sidestep this requirement, the crew may be asked to deselect the other two TACAN's via item entries to the HSD. This situation could occur if one TACAN has "bad" data and another TACAN's data is missing. Once the original lock-on requirement is met, (or bypassed), TACAN data will be used by navigation only if the crew has enabled it via the HSD "AUTO" item and the data passes a reasonableness test, or if the crew "forces" the data. This topic will be explored in detail in sections 3.4.1 and 4.4.1.

TACAN data usually becomes available at $\approx 160,000'$ on a nominal entry. The TACAN data can be used by navigation above $1500'$. At $1500'$, TACAN data is inhibited due to ground reflection problems. In the PASS, TACAN data is also inhibited from use once MLS data is acquired.

3.2.4 Air Data System (ADS). The ADS is composed of two air data probes, left and right, with two Air Data Transducer Assemblies (ADTA) associated with each probe. It is used to sense air pressures which relate to Orbiter movement through the atmosphere. These are used to compute angle of attack (α), Mach number (M), Equivalent Air Speed (EAS), True Air Speed (TAS), dynamic pressure (\bar{q}), altitude (h) and altitude rate (\dot{h}). Only barometric altitude is used in navigation. The other parameters can be used by guidance and flight control or displayed to the crew on the CRT and dedicated displays. See figure 3-5.

ADS PARAMETERS USED BY FLIGHT CONTROL	
Parameter	Use
Angle of attack, α	Compute stability axis rates for lateral channel
	Lateral axis turn coordination term
Dynamic pressure, \bar{q}	Gain scheduling for all channels
Mach number, M	Gain scheduling for all channels Switching logic to inhibit yaw jets
True Air Speed, TAS	Lateral axis turn coordination terms. Longitudinal axis gain on Nz command
ADS PARAMETERS USED BY GUIDANCE	
Parameter	Use
\bar{q}	TAEM normal acceleration limits. TAEM speedbrake control
M	TAEM bank angle command limits. Initiation of TAEM active speedbrake modulation
TAS	TAEM S-turn gain compensation. Autoland acceleration command calculation during flare to shallow glide slope
EAS	Autoland speedbrake control
ADS PARAMETERS DISPLAYED ON DEDICATED DISPLAYS	
α M EAS TAS	} AMI - Alpha Mach Indicator
$h(ALT)$ $\dot{h}(ALT RATE)$	
	} AVVI - Altitude Vertical Velocity Indicator
ADS PARAMETERS APPEARING ON CRT DISPLAYS	
α M h	} OVERRIDE DISPLAY

Figure 3-5. ADS Parameters used by Guidance, Flight Control, Dedicated Displays and CRT Displays

ADTA RM goes through a special process to select the appropriate air data parameters to be used by GNC. The selected set is called "center" air data. The individual ADTA computations for α , M, and h are displayed on the PASS Override display (figure 3-6). The Alpha/Mach Indicator (AMI) and Altimeter Vertical Velocity Indicator (AVVI) can show the average of the left ADTA's, the average of the right ADTA's and either navigation-derived (NAVDAD) air data parameters or the "center" air data values based upon the availability of air data and the AIR DATA select switches next to these dedicated displays. These types of information can be used by the crew in troubleshooting air data problems. More information on the air data system can be found in the ADS 2102 workbook.

The air data probes are nominally deployed at Mach 5. The crew verifies that the probes are deployed, as well as compares the ADTA data with navigation using the AMI and AVVI. They can also verify the individual ADTA outputs on the Override display. GNC does not begin to use air data, however, until Mach 2.5. In addition, as the vehicle goes subsonic, from $1.1 \leq M \leq 1.6$, unstable air flow is expected. During this time frame, called the "Mach jump region", navigation ignores air data. Air data is also ignored by GNC if a dilemma is encountered by RM between the individual ADTA's. Once these constraints are met, crew controls exist on the HSD to govern whether air data will be used by navigation or G&C (figure 3-7). This will be discussed in more detail in section 4.4.1.

In cases where air data is not incorporated into navigation or G&C via the HSD due to air data dilemma, probe failures, bad data, etc., the software computes the equivalent air data parameters (α , M, EAS, \bar{q} , etc.) using the current state vector and IMU attitude information. These are referred to as Navigation-Derived Air Data (NAVDAD) parameters and are used by G&C if above M 1.5. The NAVDAD data, particularly α , can be in significant error under wind or gust conditions, which can have an effect on flight control. When air data is not incorporated in G&C below Mach 1.5, "Default Air Data" is used by G&C in the PASS. Default Air Data uses a constant $\alpha = 7.5^\circ$ and defines \bar{q} as a function of VREL. The other parameters are computed as in NAVDAD. Note that even when Default Air Data is being used, NAVDAD data is being displayed to the crew on the dedicated and CRT displays. In the Backup Flight System (BFS), NAVDAD data is always used if ADTA data is not incorporated in GNC.

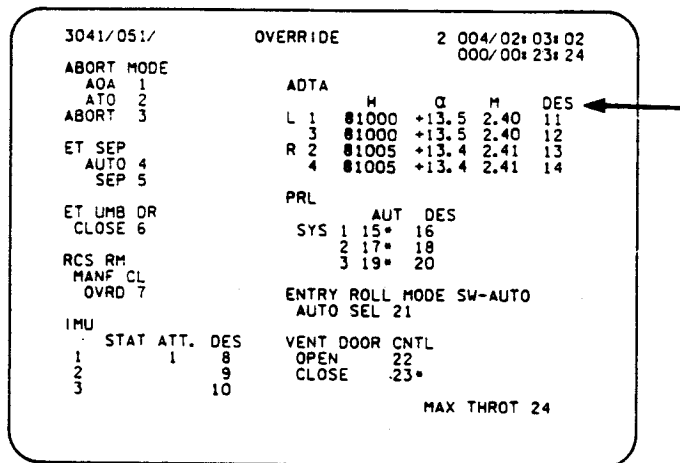


Figure 3-6. PASS OVERRIDE DISPLAY - ADTA PARAMETERS

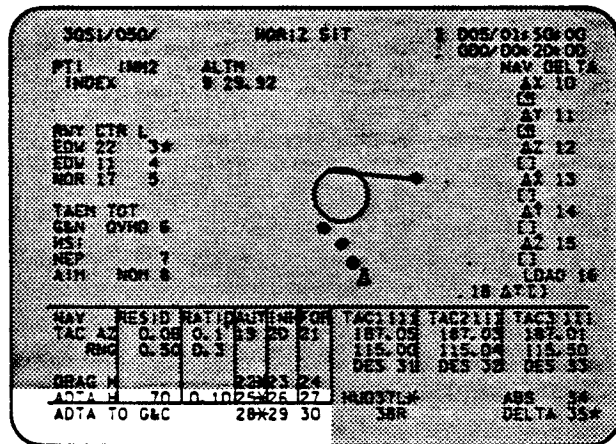


Figure 3-7. HSD - ADTA CONTROLS

3.2.5 Microwave Landing System (MLS). The three on-board MLS units determine slant range, azimuth, and elevation to the ground stations along the side of the landing site runway (See figure 3-8). The MLS data is used only by the PASS software and is available only at certain runways at Edwards, Northrup, and Kennedy Spacecraft Center (KSC). MLS data becomes available when the vehicle is within a specified azimuth and elevation beam which occurs at an altitude of approximately 18,000 ft and the range to the runway is approximately 15 n.mi. MLS RM software determines the best MLS data of the three, and this data is used to replace TACAN and ADTA data in navigation.

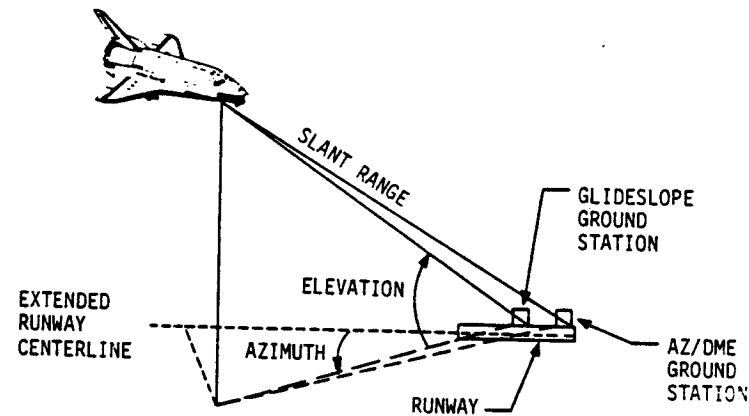


Figure 3-8. MLS Ground Stations

3.2.6 Star Tracker (ST). The Orbiter Star Tracker (ST) is an image dissector electro-optical tracking device which is used to obtain precise angular measurements of selected stars and sun-illuminated orbiting objects (targets). These measurements are used to determine the Orbiter's attitude in inertial space, and this data is used to align the IMU's. Also, the ST provides angular data from the Orbiter to a target being tracked.

Two ST's, -Y and -Z, are located next to the IMU's on a beam attached to the Orbiter's navigation base. They are slightly inclined off the vehicle axis for which they are named. The -Y axis ST centerline is approximately 10.5° from the Orbiter -Y axis, and the -Z axis ST centerline is approximately 3° from the Orbiter -Z axis. (See figure 3-9).

The ST's total field of view is $10^\circ \times 10^\circ$ square. The ST's can also be commanded to search a $1^\circ \times 1^\circ$ square field within the field of view. The ST's total error in measurement of star or target angles does not exceed 1 arc minute (1 sigma). Star or target magnitude measurement errors do not exceed an absolute maximum of 0.6 magnitude.

The ST's will acquire and track sunlit targets of 3.0 or greater magnitude. The target must be no brighter than -7.0 magnitude. Target size must be no greater than 8 arc minutes.

The ST's normally will not be used to track a target or star when the Sun is within 30° of the ST centerline, the Moon is within 8° of the centerline, the lighted Earth's horizon is within 20° of the centerline, the Earth's dark horizon is within 2° of the centerline, or if the target is in darkness. In any of the above situations, the ST centerline is said to be occulted (by the Sun, Moon, or Earth).

The primary use of the ST's is to provide accurate data on star locations to be used in aligning the IMU's. Also of importance in rendezvous is the capability of the ST to locate a sunlit target in its field of view, to provide accurate angle information to navigation, and then to track the target. This is called the target track mode for the ST. For a target with reflectivity of -7.0, the target may be acquired at up to 300 n.mi. if the lighting is correct.

The ST's are controlled onboard, using the S TRK/COAS CNTL SPEC (figure 3-10). Before commanding the selected ST to begin tracking a target, the Orbiter will be positioned so the selected ST is pointed toward the target (or navigation's estimate of the target's position). This will be done in GNC Major Mode 201 (MM 201), using the Universal Pointing display (UNIV PTG). Then, the target track (TGT TRK) item can be selected on the STRK/COAS CNTL SPEC. At this time, navigation will send the coordinates of the target, based on its calculations. The ST will go to these coordinates and will search a $1^\circ \times 1^\circ$ square for up to 4 seconds. If the target is not found because of on-board navigation errors or incorrect pointing of the ST axis, the ST will begin searching its entire field of view ($10^\circ \times 10^\circ$) for 20 seconds before giving up. If the target is not found, or if it is occulted, an appropriate message will be driven (NO TARGET, OUT FOV, etc.). This status is also displayed on the REL NAV display. If the target is found, the ST begins a track scan centered about the position at which

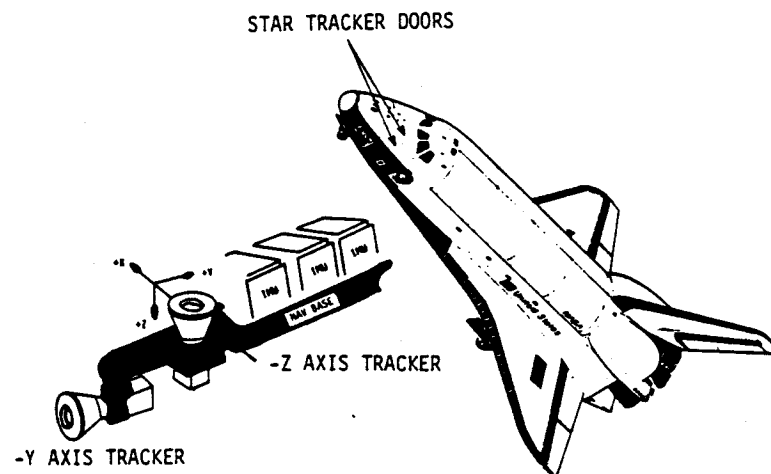


Figure 3-9. Star Tracker Location

2011/022/	S TRK/COAS CNTL	1	002/10:15:00
S TRK CNTL	-Y -Z	S TABLE	1 2 3
SELF-TEST	1 2	TRK ID	
STAR TRK	3* 4*	Δ MIN	
TGT TRK	5 6	ANG DIF	
BREAK TRK	7 8	ERR	
TERM/IDLE	9 10	SEL	17 18 19
		S TABLE CLR	20
S TRK	-Y -Z	COAS	
RECD ID	11 12	REQD ID	21
TRK ID		ΔDEG X	+1.3
S PRES		Y	-0.3
ΔANG		SIGHT MODE	22
THOLD	13 14	ACCEPT	23
SHUTTER	CL OP	CAL MODE	24
MAN OP	15 16	DES	25*
STATUS		POS	+X 26 -Z 27
		ABIAS	
		UPDATE	28 29

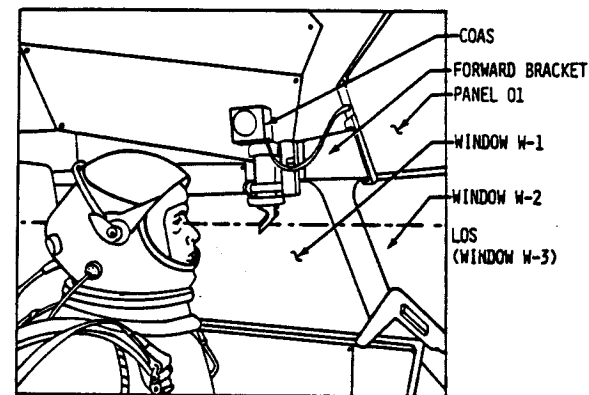
Figure 3-10. S TRK/COAS CNTL Typical Display

the target is found. The target will continue to be tracked until the target leaves the Field Of View (FOV), or until it is commanded by the crew to stop tracking via the display. The ST data received while tracking a target is used by navigation if rendezvous navigation is enabled, the ST is selected as the external sensor to be used to provide target angle data (Item 12 on the REL NAV display) and the ST data passes a nav filter test (more on this in section 4.3). Note that if the Orbiter/Target relative states are in error by over 1/2 degree, the ST will have to search a $10^{\circ} \times 10^{\circ}$ FOV for the target. In that case, it is possible that the ST could erroneously begin tracking a star instead of the target.

3.2.7 Crew Optical Alignment Sight. The Crew Optical Alignment Sight (COAS) is an optical device which is used to manually sight stars or a target. The COAS is used to align the IMU's when their misalignment is greater than the ST's can handle, and to verify that the correct star or target is being tracked by the -Z tracker. Also, the crew can use the COAS to obtain the range and Line-of-Sight (LOS) angle to a target, as well as obtain a qualitative idea of the range rate and target LOS rate from the target. How well the crew will be able to see the target against the lighted reticle is of concern and depends upon the size and lighting conditions surrounding the target. It is thought that the crew will be able to see the target at distances up to 30 n.mi.

The COAS may be mounted in two locations defined by the vehicle axis along which it sights, as shown in figure 3-11.

- +X above the commander's window
- -Z next to starboard overhead window.



FORWARD USE LOCATION
(FLIGHT DECK)



Figure 3-11. COAS Locations

Before COAS data can be incorporated into navigation, several steps must be taken. The COAS must be mounted in either the +X or -Z position. Next, the STRK/COAS CNTL SPEC (figure 3-10) must be called. Inputs to the display are then made to specify what target is to be sighted, as well as to identify to the software the position in which the COAS is mounted (+X or -Z). An input must also be made to enable the COAS mark function (called the COAS SIGHT mode on the display-Item 22). In this mode, the ADI ATT REF pushbutton is used to mark the target. If the -Z ST is already tracking the target, a readout (X, Y) will appear on this display to inform the crew of the ST-determined location of the target in the COAS FOV. In any case, the crew must ensure that the Orbiter is maneuvered so that the target is in the COAS FOV. Manual maneuvers are then made so that the target will cross the center of the reticle. (See figure 3-12).

When the target crosses the center, the crewmember depresses the ATT REF button; i.e., takes a mark. This causes the software to store the gimbal angles of the three IMU's. However, the software will not process these angles until an accept command, Item 23 Exec, is received. Thus, several marks may be taken until the crew is satisfied that the target was properly centered at the instant the ATT REF button was depressed. Even following an ACCEPT command, the COAS data will not be utilized to update the Orbiter (or target) state vector unless rendezvous navigation (in which external sensor data is allowed) has been enabled, COAS has been chosen as the source for target angle data via the REL NAV display (Item 14), the COAS data is less than 2 minutes old, and the COAS data has passed a NAV filter test.

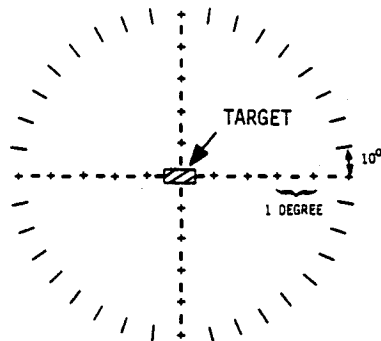


Figure 3-12. COAS Reticle Pattern

3.2.8 Rendezvous Radar (RR). The Rendezvous Radar (RR) provides automatic target detection, acquisition, and tracking. It assists in reducing target location uncertainties during rendezvous maneuvers. The radar tracks a target automatically to determine range, range rate, roll (azimuth), and pitch (elevation) relative to the Orbiter, as well as inertial target angle rates.

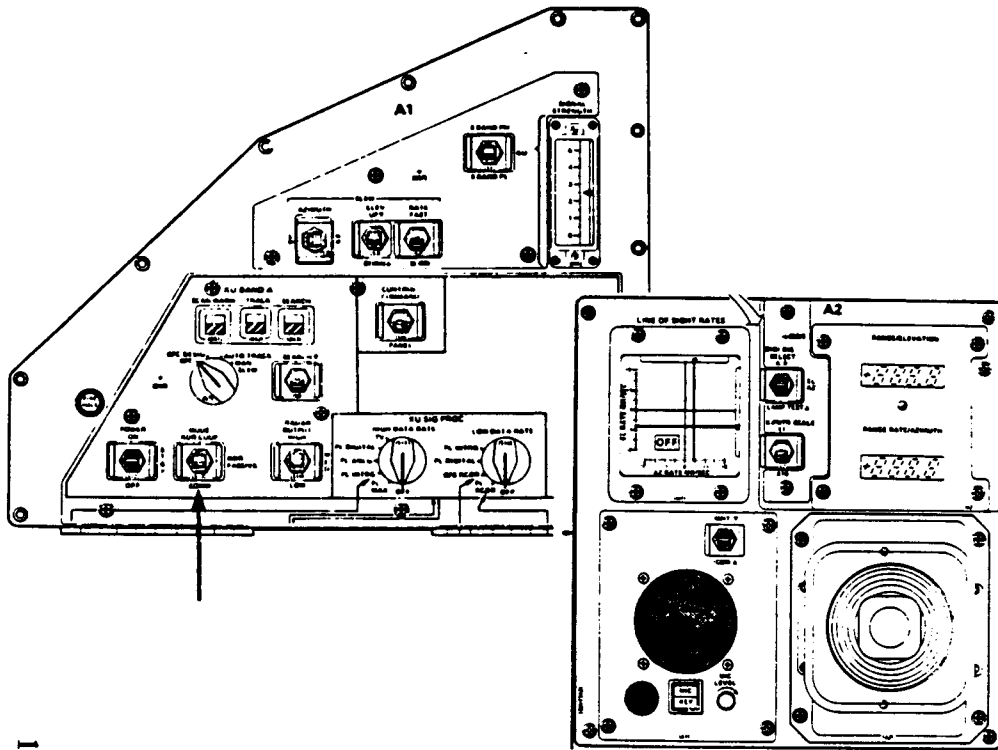
The RR operates as part of the Ku-band system which is controlled by the SM (Systems Management) GPC. It should be noted that the Ku-band system is a dual purpose system which will be used as either a wide band communications system for data interchange with the ground or as an RR. The functions of Ku-band communications and radar are not available simultaneously. Whether the Ku-band system is to be used for COMM or for rendezvous radar applications depends upon the KU-BAND A MODE switch on Panel A1 (Figure 3-13). In addition, in order to be used as a RR, Item 2, KU ANT ENA, on the REL NAV display, must be selected. This causes the GNC GPC's to send target-angle pointing data to the SM GPC (using the Inter-Computer Communication (ICC) data bus). The SM GPC uses this data to point the Ku-band antenna at the target (instead of a TDRS satellite). Note that when the KU ANT ENA item is selected on REL NAV, the Ku-band system cannot be used for ground communications through the TDRS system, regardless of the position of the KU-BAND A Mode switch. The capability does exist, however, to go to the KU-BAND COMM mode and establish communications with a target.

The antenna associated with the Ku-band system is contained in a deployable assembly, which is mounted on the starboard sill longeron. It is rotated in a roll-pitch Euler angle sequence (also known as azimuth-elevation, respectively). Because of the design, there are no pure azimuth or elevation movements of the antenna.

For early STS flights, the RR will only be used to track passive targets, i.e., targets which do not have an active transponder. The radar will detect, acquire, and track passive targets of 1 sq. mi. radar cross-section from about 100 ft to 10 n.mi. A greater cross-section will increase the maximum range but not decrease the minimum. The maximum unambiguous range is 27 n.mi.

In addition to the possible limitations imposed by the short target acquisition distance, the RR-detected LOS angle rates may be in error at short ranges where the subtended angle of the target exceeds one-half of the beam width of the radar (about 1.5°). Also, the range and range rate accuracy requirements for the RR are on the order of 78 feet in range (at distances under 1.3 n.mi.) and 1 ft/s in range rate in the worst case. It is thought that the radar will be better than the requirements stipulate; however, the actual performance values are currently unknown. The RR angle data should have one-sigma error less than 1° .

As mentioned earlier, the RR system has its displays and controls on Panels A1 and A2 in the aft station. It can be used in either a GPC controlled mode or one of several manual modes (GPC DESIG, AUTO TRACK, MAN SLEW). In the GPC mode, assuming KU ANT ENA is selected on REL NAV and the Ku-band system is in the RDR passive or COOP mode, the software will command the RR to scan a specified area



around the expected target location until it finds and "locks on" to the target. At this time it displays range, range rate, elevation/azimuth angles and rates on panel A2 and the REL/NAV display. The RR range and range rate data will be used to update the Orbiter and target state vectors if, via the REL NAV display, rendezvous navigation is enabled, the navigation filter is in AUTO or FORCE, and the data pass a navigation filter test. The RR angle data are utilized if the above criteria are met and the RR is selected as the navigation source for target angle data (Item 13 on REL NAV).

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Figure 3-13. RR Displays and Controls (Panels A1, A1)

3.3 STATE VECTOR PROPAGATION/SUPER G ALGORITHM

During the mission, navigation cyclically (once every 3.84 seconds) recomputes the current state vector based upon the previously computed state vector. This is referred to as state vector propagation. To do this, it uses the standard equations of motion (EOM) expressed in a truncated Taylor series expansion in which it assumes that the rate of change in acceleration on the vehicle is constant. It also uses a model of gravity and either the acceleration sensed by the IMU's if in powered flight or the drag acceleration model if in coasting flight. The numerical algorithm used by navigation is called Super-G. It was designed to be computationally fast yet retain adequate accuracy to accomplish mission goals. The algorithm essentially works as follows:

1. Given the state vector and gravitational acceleration from the last cycle, estimate a new position vector this cycle using either modeled drag acceleration or IMU sensed acceleration in the simplified Equation Of Motion (EOM) ($S = S_0 + V_0 t + \frac{1}{2} a_0 t^2$)
2. Compute gravity at the new position.
3. Using the change in gravity (ΔG) from the past to current cycle, recompute the new position and velocity vectors using an additional term in the EOM which assumes a constant $\frac{\Delta G}{\Delta t}$.

The name Super-G comes from the technique of estimating the new state vector position in order to get a better idea of the change in gravity over time and then using this to recompute the new state vector. See figure 3-14 for a more detailed explanation of the algorithm. Note that if modeled drag acceleration is used in the algorithm, the more complex fourth order gravity model is used. If IMU sensed drag acceleration is used, the J2 gravity model is incorporated in the algorithm.

Whether modeled or IMU-sensed drag acceleration is used depends upon several factors. In OPS 1, 3, and 6, IMU-sensed drag acceleration is used during thrusting or atmospheric flight as determined by the sensed acceleration exceeding a specified threshold level (typically 1000 μg 's). During coasting flight, there is concern that the state vector would be polluted by using small IMU-sensed accelerations due to the known low-level errors in the IMU's (particularly accelerometer bias). Also, the nav base on which the IMU's are strapped is located 55 ft forward of the Orbiter c.g. This results in erroneous small translations being sensed when a pure rotation about the Orbiter c.g. is made. The threshold level, then, is set at a level which should prevent these erroneous translations and the low-level IMU-sensed acceleration errors from polluting the state vector. When IMU-sensed acceleration does not exceed the threshold, such as in coasting flight, modeled drag is used.

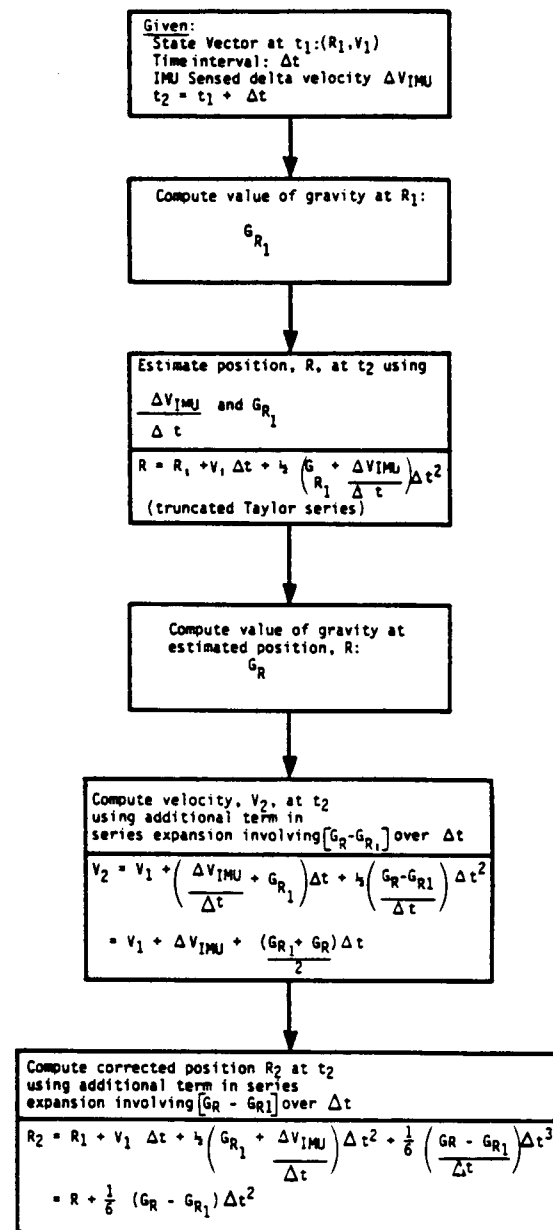


Figure 3-14. Super-G Algorithm Using IMU Sensed Acceleration

During OPS 2 and 8, a more complex system is used to provide the more accurate navigation required for the extended periods of time during orbit and to account for the smaller sensed accelerations which result from vernier jet firing. This includes a correction in the software to convert the nav base-referenced IMU accelerations to Orbiter c.g. referenced accelerations. This eliminates the errors caused by the c.g. to nav-base lever arm effects discussed earlier. This computation is made based upon the current Orbiter angular rates as estimated by the Orbit DAP. Also included in OPS 8 and Major Mode 201 is the capability for the crew to inhibit navigation from using IMU-sensed acceleration via the "AVG G" item located on the REL NAV display (figure 3-15) and the FCS DED DIS C/O (figure 3-16). When AVG G is disabled, coasting flight nav is used, in which only modeled drag acceleration is used. When AVG is enabled, as it typically is, powered flight nav is used. In this mode, IMU-sensed acceleration is used based upon the threshold tests. Note that AVG G is initialized enabled on the transition to OPS 801 or 201. In Major Mode 202, AVG G is always enabled. The threshold tests used by powered flight nav in OPS 2 and 8 include the following:

1. A test for an OMS burn in progress and for non-propulsive thrusting. In this test, if the sensed acceleration over the last nav cycle (corrected to the Orbiter c.g.) exceeds a pre-determined value, it is incorporated in the state vector. This threshold value is initialized to 1000 μ g. The 1000 μ g value was selected based upon expected uncompensated IMU accelerometer biases. The crew can view and/or modify this threshold in OPS 2 via the Δ V THRESHOLD item on the IMU ALIGN display (figure 3-17). Note that the displayed value on this display is in terms of acceleration multiplied by time. Since the nav cycle is 3.84 seconds, 1000 μ g appears on the display as 3840. Changes to the initial threshold value have not been made on previous missions and there are currently no plans to use this capability in the future.

2. A test for translations resulting from RCS jet firings. In this test, if RCS jet firings occur, the IMU-sensed acceleration is used to propagate the state vector if the value of the acceleration accumulated over the jet firing interval exceeds a threshold. This threshold is based upon the predicted IMU accelerometer biases and is currently set at .09 fps. By comparing the IMU-sensed acceleration accumulated over the jet firing interval to a threshold, low level translations which would not exceed the 1000 μ g test threshold can be detected. Unfortunately, the .09 fps threshold is too large to detect vernier RCS jet uncoupled thrusting. (Uncoupled thrusting refers to the situation in which a commanded rotation results in both a rotation and a small translation due to the placement of the jets). This could lead to a 2000' error per rev following the maneuvers required to accomplish a star alignment using the .2 deg/sec rotation rate in the vernier RCS system.

If AVG G is enabled but the sensed IMU accelerations do not pass either of the two threshold tests, modeled drag is used in state vector propagation. Note that originally only test 1 was made. Test 2 was added in version 20 flight software to correct for errors which were found to accumulate in nav on orbit.

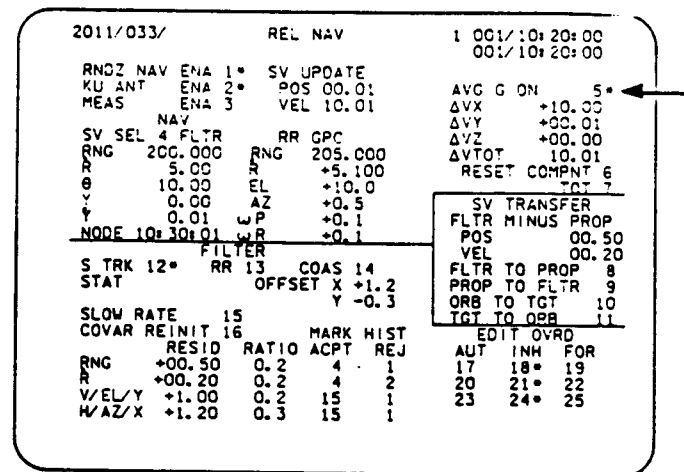


Figure 3-15. REL NAV - AVG G ITEM

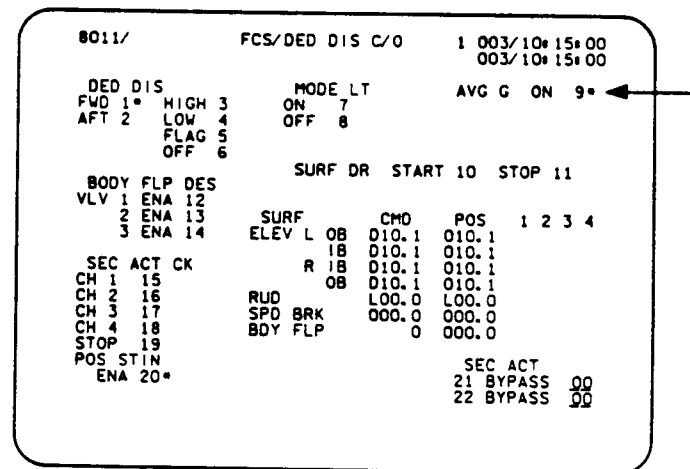
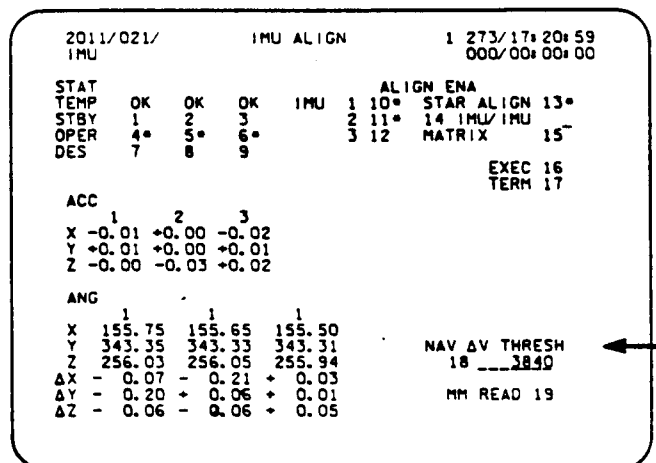


Figure 3-16. FCS/DED DIS C/O - AVG G ITEM

Figure 3-17. IMU ALIGN DISPLAY - NAV ΔV THRESHOLD

In the BFS, only one state vector is propagated during the flight. It is computed based upon the data from the IMU selection filter or modeled drag. Similarly, in PASS OPS 1, 2, 6 and the final part of OPS 3 (after MLS acquisition), only one Orbiter state vector is propagated. Prior to MLS acquisition in PASS OPS 3, however, navigation computes three separate state vectors - one associated with each IMU. Then, a selection process between the three state vectors is made to choose the navigation selected state vector. If all IMU's are considered to be good, the selected state vector will be computed via a component-by-component mid value selection process. If one IMU is failed, the selected vector will be computed as the average of the remaining two valid state vectors. Of course, if only one IMU is considered good, its associated state vector will be used. In any case, the selected state vector is subsequently improved with external sensor data when it becomes available. "Three-state navigation" is used to give more protection to the on-board navigation system in case of multiple IMU failures. In the worst case, if one IMU failed and the second IMU had degraded data, the selected state vector would be based upon the average of the degraded IMU's state vector and the remaining good IMU's state vector, and thus would be in error. Upon deselection of the degraded IMU, the selected state vector would become the state vector computed independently based upon the good IMU. Thus, it would not have been polluted by the degraded IMU.

In the PASS during rendezvous, a target state vector is also computed using the Super-G algorithm and modeled drag acceleration.

3.4 ERRORS IN STATE VECTOR PROPAGATION

The state vector propagation techniques discussed thus far were designed to be computationally quick and minimal in computer storage requirements yet provide the necessary accuracy to accomplish mission goals. As there are built-in errors in the state vector propagation algorithm due to inaccuracies in the models (drag, gravity), possible bias in IMU data, and in the simplification of the equations of motion, the on-board maintained state vector does begin to diverge from the real-world state vector with time. This is corrected during flight using state vector updates calculated by mission control based upon highly accurate tracking data. In addition, during entry, the software can use drag altitude, TACAN, ADTA and MLS data to improve the state vector. During rendezvous, ST, or COAS data may be used to add accuracy to either the vehicle or target state vector. However, these external sensors also may have errors associated with their data. To ensure that the state vector could not inadvertently become polluted by incorporating erroneous sensor data, and to ensure the proper weighting of the sensor data on the state vector, a scheme called Kalman filtering is used to "filter" and "weight" incoming data. This process and state vector updates will be discussed in the following sections.

3.4.1 Kalman Filter. Functionally, the Kalman filter is a mechanism wherein inertial data and external measurements are blended in an optimum manner in order to provide a more accurate estimate of vehicle position and velocity. To do this, a matrix is maintained which represents the current uncertainties in the vehicle state. The diagonal elements represent what is called the variance in the state. This is the square of the statistical estimate of one sigma error in the vehicle position or velocity. The off-diagonal elements represent the cross correlation, or covariance, of the state errors. These would show how errors in different components of position or velocity affect the other components. This is the origin of the term covariance matrix. Another way of thinking of the covariance matrix is that it represents the "cloud of uncertainty" about the state vector. The Kalman filter, and thus the covariance matrix, are only used during entry (OPS 3, 6) and rendezvous phases of flight. When rendezvous navigation is active, the covariance matrix will be used with respect to either the Orbiter or the target, depending upon a premission determination of which data is assumed to be most accurate. This will be discussed in more detail in the section on rendezvous navigation (4.3).

The general operation of the Kalman filter during entry is as follows:

1. Propagate the state vector to time, t , using Super-G algorithm
2. Propagate the covariance matrix to time, t , using a model of expected noise based on the types of data sources (e.g. TACAN)
3. Get measurement, M , at time t (such as TACAN slant range)
4. Using the propagated state vector, compute the expected measurement, M_e .
5. Form the residual, $\Delta M = M - M_e$. This will be displayed to the crew on the HSD (figure 3-18) in the RESID column.

NAV	RESID	RATIO	AUTO	INH	FOR
TAC AZ	1.1	0.1	19	20	
RNG	10.3	0.0			
DRAG H			19	23	24
ADTA H	1000.0	0.1	25	26	27
ADTA TO G&C			28	29	30

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Figure 3-18. HSD NAV EDIT TEST

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- Using the propagated covariance matrix, compute the maximum acceptable measurement error, ΔM_A , at this time. This will be used to prevent the Kalman filter from using bad sensor data.
- Form ratio, $\frac{\Delta M}{\Delta M_A}$. This will be displayed on the HSD in the RATIO column.
- Check the HSD for the AUTO/INHIBIT/FORCE (A/I/F) selection for the type of measurement.
 - If in INHIBIT, ignore the measurement
 - If in AUTO, perform the residual edit test. In this test, if the ratio ≥ 1 , the data is not used, i.e., it is edited. If the ratio is < 1 , the data is used. If the ratio is greater than one n times, a "!" will appear next to the ratio on the HSD. The "!" will only go away after the ratio passes the test "n" times (n is usually 3). Note: The TACAN also must pass a 40° glitch filter.
 - If in FORCE, the measurement data will be used regardless of the ratio.
- If the measurement data is to be used, calculate its "weight" on the state vector based upon the covariance matrix.
- Update the state vector and covariance matrix using the measurement data.

Before any external sensor data is available, the covariance matrix is said to be "open." This means that the first external sensor data to be received, typically drag altitude, can be quite different from nav and still be able to pass the residual edit test. For example, initially, drag altitude can differ from navigation by 80,000 ft and still pass the residual edit test and thus be used to update navigation (if in AUTO). Once drag altitude is incorporated, however, the covariance matrix (the "cloud of uncertainty") begins to "shrink." This makes the residual edit test, which is a sensor reasonableness test, more stringent. It also results in less "weight" being placed on later external sensor data in updating the state vector. In other words, as data is incorporated from each nav sensor, the accuracy of the state vector improves, which in turn improves the state vector's credibility over subsequently received sensor data.

During entry, the covariance matrix is reinitialized when a delta state vector update (one in which the crew or ground updates the state vector by "delta" position or velocity - discussed in section 3.4.2.2) is done. Reinitialization of the covariance matrix "opens" it and increases the weighting of external sensor data. Note that simply forcing data does not affect its "weight" on the state vector. Thus, as an extreme case, suppose navigation incorporates external sensor data such that the covariance matrix shrinks. Suppose then that navigation begins to diverge due to erroneous sensor data. When good sensor data is acquired, a "FORCE" would cause the software to use the new sensor's data but might not give it enough weight on the state vector to stop it from diverging. In such a case, a "zero" delta state vector update could be

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performed (zeros are loaded as the deltas) prior to forcing the data which would reinitialize the covariance matrix.

When rendezvous navigation is active, there are other ways to reinitialize the covariance matrix. This will be discussed in section 4.3.

3.4.2 State Vector Updates. The MCC maintains an accurate knowledge of the vehicle's position and velocity using radar tracking data and sophisticated state vector prediction computations. It also receives the Orbiter's on-board computed state vector via the downlist. From these, it keeps track of the difference between the two. Depending upon phase, the ground will attempt to correct the on-board state vector when the position or velocity delta exceeds a specified magnitude. For example, when the vehicle altitude is less than 130K ft during entry, the state vector is updated if it has velocity component errors > 75 fps or downrange/crossrange/altitude errors > 6000 ft.

It is possible for the MCC to uplink either a completely new state vector (a "whole state vector update") or simply deltas to the on-board state vector (a "delta" state vector update). Which is used depends on the current flight phase. In addition, if command uplink were unavailable during flight for some reason, it may also be possible for the MCC to uplink by voice the required changes to the state vector and have the crew implement the update via CRT inputs. The HSD is used for a delta state update in OPS 1, 3, or 6. The GPC MEMORY display is used for a whole state vector update in OPS 2 or 8 (this is a complex, time consuming procedure). There is also a procedure available in OPS 2 for the crew to transition to OPS 3, do a delta state vector update and then transition back to OPS 2.

While both the whole and delta state vector update capability exists for both the PASS and BFS, the pre-engaged BFS typically has its state vector updated using a PASS to BFS state vector transfer as opposed to a direct uplink from the ground. This will be discussed in section 3.4.2.3.

Another scheme using TACAN data is being incorporated between STS 15 and STS 24 to provide an independent on-board method of updating the state vector during on-orbit operations.

3.4.2.1 Whole State Vector Update. In OPS 1, 2, and 3, it is possible for the MCC to uplink a new state vector. The Orbiter must have TDRS communication or be over a ground station with S-band capability in order for the uplink to be possible. The whole state vector update capability is not normally used during powered or atmospheric flight as it involves taking the uplinked state vector and "predicting" it forward or backwards to the current time without using any IMU acceleration information. This can lead to errors in the new state if the vehicle is accelerating. To avoid this, delta state vector updates are done during powered and atmospheric flight.

In general, the on-board state vector propagation scheme can maintain the vehicle state accurately enough to meet entry guidance requirements for three to four hours. Periods of high Reaction Control System (RCS) activity (attitude and small translation maneuvers), on-board water dumps and Auxiliary Power Unit (APU) venting can increase the rate at which the state vector diverges. State

vector updates are made periodically to maintain adequate on-board navigation to provide contingency deorbit capability for the case that ground communication is lost. In addition, state vector updates may be planned to satisfy mission or payload requirements. As an example, during Orbital Flight Test (OFT) flights, whole state vector updates were made every 2 to 13 hours as well as during the last rev prior to deorbit.

A whole state vector update is accomplished by uplinking all six components of the new state vector plus a time tag. A special navigation software algorithm, the precise predictor, is used to propagate the uplinked state vector forward or backwards to the current time. As mentioned earlier, no IMU data is used. Next, this state vector is substituted for the current on-board state vector.

If it is not possible to uplink a state vector, there exists on-board a GMEM READ/WRITE procedure in which the crew loads the new state vector in the GPC MEMORY display (figure 3-19), one computer address at a time, based upon a voice uplink of the new state vector. As this procedure is time consuming and a crew error could have serious results, it will be used only if the situation is critical.

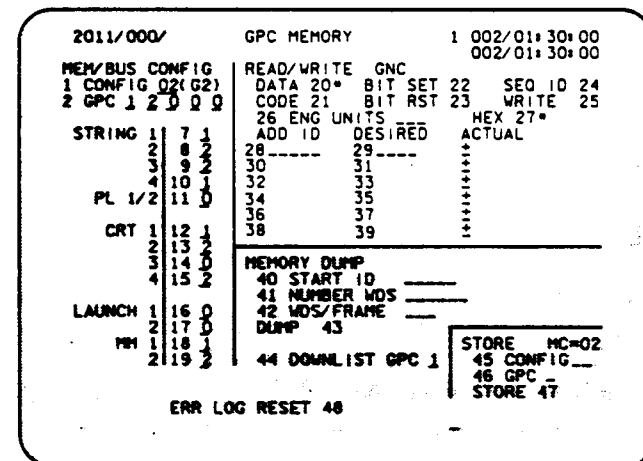


Figure 3-19. GPC MEMORY DISPLAY STATE VECTOR UPDATE

3.4.2.2. Delta State Vector Update. During OPS 1, 3 and 6, it is possible for the MCC to send uplink commands to update the position and/or velocity components of the state vector by the difference, or delta, between the ground and on-board computed state vectors expressed in runway coordinates. To do this, mission control propagates the Orbiter's state vector to a specified future time in two ways. One way propagates the downlisted state vector (as computed on-board). The other propagates the state vector which is derived from ground tracking data. Mission control computes the delta between these two values at the specified future time and uplinks the delta such that the software will load it near the specified time. This increases the accuracy of the update in case the ground and on-board computed states are diverging.

Another capability available in OPS 3 is to correct downrange error by loading a delta time (ΔT) in the on-board state vector. This is referred to as a " ΔT Update". Essentially, this technique tells the software that the present state vector should really be the state vector a few seconds earlier or later. Because pre-TDRS, this technique was typically done over the GUAM site post-blackout during entry, it is sometimes referred to as the "Guam trick."

It is also possible for the crew to enter a delta state vector update via the HSD. This would only be done if the ground loses command uplink capability while retaining voice uplink and downlist capability. See figure 3-20 for the crew procedures to perform a delta state update. Note that the ground will typically give a time at which the crew is to execute the "load" of the delta. As mentioned before, the crew should execute the update as close to this time as possible to increase the accuracy of the new state for the case where the on-board and ground computed state vectors are diverging.

NAV DELTA PAD

ΔX 10	()					
ΔY 11	()					
ΔZ 12	()					
ΔX 13	()					
ΔY 14	()					
ΔZ 15	()					

```

3041/050/ NOR IZ SIT 1 003/014 30:00
                                000/004 15:00
PT1 INRZ ALTH NAV DELTA
INDEX 9 23 32
R/V CTR L
EDW22 3*
EDW17 4
NOR17 5
TAEN TGT
GPH OVHD 6
Y51
CEP
AIR NOR 8
                                18 ATC
NAV RESID RAYTONUNNFOR TAC 111TAC2111 TAC3111
TAC AZ 11.0 0.0 13 ED 21 * 1.1 * 1.0 * 0.9
RNG 11.0 0.1
                                * 11.1 * 10.9 * 11.0
DRAG H 10.0 0.0 22-23 24
                                DES 31 DES 32 DES 33
ASTA H
                                HJ037L ABS 34
ADTA TO GRC 24 23 00 30R                                DELTA 35
  
```

For Δ STATE UPDATES that include VELOCITY components (MCC call):
 P, R/Y - CSS
 DRAG A/I/F - I, then
 back to AUTO after MCC
 calls Δ STATE incorporated

V = 10.5K *** BUC AOS (UPLINK - ENA) *****

CREW-PERFORMED DELTA STATE PROCEDURE:

- Enter Δx , Δy , Δz , $\Delta \dot{x}$, $\Delta \dot{y}$, $\Delta \dot{z}$ values in Items 10-15 (these are in runway coordinates). (The sense of these inputs is ground estimated minus on-board computed).
- Verify that the correct values are entered
- Load the deltas with an Item 16 EXEC. Items 10-15 will blank after update is complete
- A similar procedure would be used in OPS 3 to LOAD a ΔT update. In that case, the ΔT is entered via Item 18 and loaded with an Item 16 EXEC.

Figure 3-20. Delta State Vector Update

Note that the ground has the crew select Control Stick Steering (CSS) and inhibit drag altitude prior to execution of a delta state which involves velocity components. Selection of CSS is done to prevent the possibility of there being any excessive transient maneuvers caused by the delta velocity. Inhibiting on-board drag altitude updating is done to ensure that the ground can make a valid computation of the propagated velocity errors (recall that the way a delta update is made involves propagating the on-board and ground radar computed vectors to a future time, without the benefit of any drag altitude updates, and thus computing the deltas to be uplinked at that future time). Any kind of a delta state update performed near the TAEM interface also requires the crew to go CSS to avoid potential transient maneuvers in this critical flight regime.

Per the current flight rules, the MCC will send a velocity update for an error > 75 fps in any component and a position delta state vector update for the following errors:

FOR RTLS	Δ POSITION (FT)			Δ FOR NOMINAL END OF MISSION	Δ POSITION (FT)		
	X	Y	Z		X	Y	Z
H > 100K FT.....	18K	18K	6K	H > 130K FT.....	48K	48K	12K
H < 100K FT.....	6K	6K	3K	H < 130K FT.....	6K	6K	3K

Also note that a delta state update made in OPS 303 results in the Range to Entry Interface (REI) and Time to Free Fall (TFF) values being recomputed as seen on the DEORB MNVR COAST display.

Of interest is that any time a state vector update is accomplished in OPS 3, the covariance matrix is reinitialized. This makes it easier for nav sensor data to pass the residual edit test and also gives nav sensor data more weight in updating the state vector. In addition, in three-state navigation (PASS OPS 3 prior to MSL acquisition), the three state vectors are reset to the last selected state vector prior to the delta state being incorporated. This characteristic is used in certain malfunction recovery procedures. For example, in OPS 3, suppose IMU 1 is commfaulted (data loss) due to an Multiplexer/Demultiplexer (MDM) FF1 failure, and that MDM FF1 is later recovered. The I/O ERROR FF1 pocket checklist procedure will call for a ZERO DELTA STATE VECTOR UPDATE. This means that the crew will LOAD a zero update via the HSD (all zeros in items 10-15 followed by an ITEM 16 EXEC). This results in the state vector associated with IMU 1, (which is erroneous due to the previous lack of data) being updated to the last selected state vector value (which was the average of the state vectors associated with IMU's 2 and 3).

3.4.2.3 PASS TO BFS State Vector Transfer. The capability to update the BFS state vector using whole and delta state vector updates exists in the BFS as in the PASS. In addition, the capability exists for the BFS to update its state vector using the PASS state vector, assuming the BFS is "tracking" the PASS. Cyclically, the PASS GPC's send "transfer data" to the BFS GPC. This transfer

data includes the current PASS state vector. Usually, the BFS ignores this information. However, in two cases, the BFS uses this data to update its own state vector. One case involves a manual crew input to the BFS HORIZ SIT display (figure 3-21). When an Item 17 PASS/BFS SV XFER is entered, the BFS snaps the next PASS state vector it receives and performs a reasonableness test. This test verifies that the PASS state vector has a reasonable position vector, R, ($|R|$ is between the polar radius of the earth and 500 n.mi. orbital altitude), velocity vector, V, ($0 < V < 30,000$ fps) and time tag. If the PASS state vector fails this test, the fault message "RM FAIL XFER" will be annunciated by the BFS. If it passes the test, the BFS computes the delta between it and the BFS state vector and displays it in UVW coordinates (not the usual runway coordinates) to the crew in Items 10-15. The crew can observe the delta and make a decision on whether to actually incorporate these deltas in the BFS by executing a "LOAD" via an Item 16 EXEC. While waiting for the "LOAD," the BFS propagates both the PASS and BFS state vectors using the usual super G algorithm. Note that only the BFS state vector is updated with sensor data, such as drag altitude, assuming it was being incorporated in nav. The delta display on HORIZ SIT is cyclically updated to the difference between the BFS-propagated PASS and BFS state vectors (the PASS transfer data is only used once). When the crew executes a "LOAD," the BFS will substitute the propagated PASS state vector for its own. Thus, in general, the crew should not delay executing the LOAD of the PASS state vector. After the BFS completes its loading of the PASS state vector, the displayed deltas will zero. A second entry of ITEM 17 EXEC zeros the deltas. Thus, if the crew decides not to "load" the deltas, they could zero the deltas by re-entering ITEM 17 EXEC.

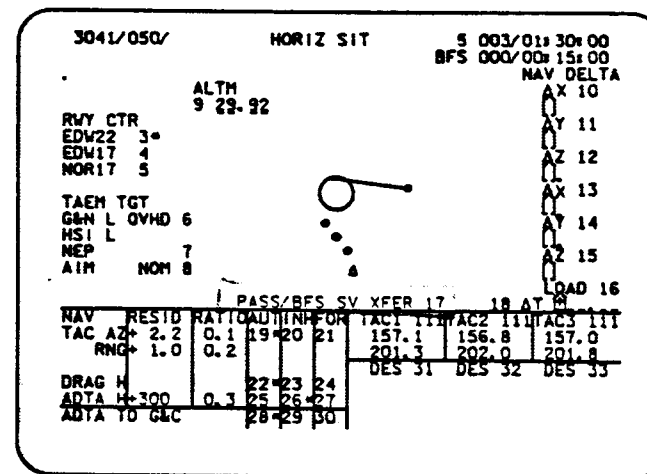


Figure 3-21. BFS HORIZ SIT DISPLAY - PASS/BFS SV XFER

SECTION 4
NAVIGATION BY MISSION PHASE

The other case in which the pre-engaged BFS uses the PASS state vector is on transition to Major Mode 301 (from Major Mode 104, 105, 106, or OPS 0). Once again, it snaps the PASS state vector and performs the reasonableness test. If the PASS state vector fails the test, "RM FAIL XFER" is annunciated and the BFS uses the last state vector stored at the end of OPS 1 unless it has been reloaded with software from mass memory. In that case, a default state vector is used. If the PASS state vector passes the test, it will be substituted for the BFS state vector.

3.5 USER PARAMETER PROCESSING (UPP)

Navigation state propagation advances the navigation state vectors at relatively large intervals of time (typically once every 3.84 seconds), at the end of which external sensor measurement data may be incorporated if appropriate. Since other software users such as guidance, flight control, and displays require a knowledge of the state vector at shorter intervals, another software module, called User Parameter Processing (UPP), is called in to integrate the equations of motion over shorter intervals of time. To do this, it takes the most recent state vector, the last computed value for gravity, and either IMU-sensed delta velocity (if above the threshold) or modeled drag acceleration, and quickly computes an updated state vector using the "Average G" technique. In this technique, if s_0 is the initial position, v_0 the initial velocity, a_0 the IMU or modeled drag acceleration, g_0 the value of gravitational acceleration, and t the time interval, the new position, s_1 , is computed as:

$$s_1 = s_0 + v_0 \Delta t + 1/2(a_0 + g_0) \Delta t^2.$$

The value of gravity, g_1 , at position s_1 is computed and the average of g_0 and g_1 is used to compute the velocity, v_1 , at position s_1 :

$$v_1 = v_0 + a_0 + 1/2(g_0 + g_1) \Delta t.$$

This process is repeated until the next nav cycle when navigation computes a new state vector.

The components of the state vector generated by UPP are transformed into other frames of reference as needed by other software users. For example, it expresses positions in terms of reference frames related to landmarks, radar beacons, and way points to aid the crew's interpretation of the data. In addition, it derives aerodynamic parameters from the state vector to be used by guidance, flight control, and displays.

Thus far, the software functions used in navigation have been discussed in general terms. During different mission phases, variations on these exist. In addition, crew visibility into the nav state and ability to interact with navigation varies between mission phases. These topics will be addressed in subsequent paragraphs.

4.1 ASCENT NAVIGATION

Ascent navigation is initialized at T-8 seconds, at which time the geodetic location of the navigation base (ϕ, λ, h) and the Earth's angular velocity vector are transformed to an M50 state vector. This vector is then propagated using the Super-G algorithm throughout the ascent flight phase, using either sensed ΔV 's from the IMU's, or modeled drag to account for non-gravitational accelerations. Ascent nav uses only the set of IMU ΔV 's obtained from IMU RM. No external measurements are incorporated and no covariance matrix is propagated. At the end of MM 106, the state vector, IMU ΔV 's and time tag are saved to carry over into the next OPS sequence (OPS 2, nominal; or OPS 3 AOA or OPS 3 in the BFS) for initialization.

Pre-MECO, the MCC monitors the on-board PASS and BFS navigation performance and is prepared to make state vector corrections as required to protect MECO conditions (a small nav error at MECO could cause significant errors in the vehicle's trajectory). If necessary, a delta state update to the PASS will be done by the ground. Assuming the BFS is not engaged, the MCC will not send a delta state correction directly to the BFS. Instead, they will request the crew do a PASS/BFS SV FER. Of course, if the BFS were engaged, the MCC would directly update the BFS.

Prior to each of OMS 1 and OMS 2, the MCC will determine if a whole vector update is required. If a state vector update is made, the crew will be asked to reload the OMS 1 or OMS 2 targets to check the results based upon the corrected state vector. As before, the BFS state vector would be updated with a PASS/BFS SV XFER if the BFS were not engaged.

As no external sensor data is available during ascent, the crew has little insight into the health of the on-board nav system.

4.2 ORBIT (NON-RENDEZVOUS NAVIGATION)

Orbit navigation is active in OPS 2 and 8 when rendezvous navigation is not selected. Once again, the Orbiter state vector is propagated with the Super-G algorithm. As discussed in section 3.3, the crew has the capability in Major Modes 201 and 801 to prevent navigation from using IMU-sensed acceleration by disabling the AVG G item on the REL NAV display if in 201 or the FCS/DED DIS C/O display if in 801. Normally, however, AVG G will remain enabled and, in Major Mode 202, it is always enabled. In OPS 2, the crew will be able to monitor translations via the thrust monitor portion of the REL NAV display. This shows the velocity gained along the respective X, Y and Z body axes. It also displays the total accumulated velocity along all axes. The component values increment

or decrement based upon the direction of the sensed translation while the Δ VTOT value represents the total sensed translation and thus always increments. In fact, it counts up even during coasting flight at approximately 1 fps/min. The individual components or the Δ VTOT may be reset to zero using the "RESET COMPNT" items on the display.

As mentioned in section 3.3, in both OPS 2 and 8, the accelerometer data received from IMU RM has been corrected to an Orbiter c.g.-centered reference frame instead of the IMU nav base-centered reference frame.

Recall that powered flight navigation is enabled in MM 201 and 801 when AVG G is selected and is always enabled in MM 202. Powered flight navigation uses IMU-sensed acceleration if it exceeds a threshold (typically 1000 μ g's) which will occur during an OMS or RCS translation. It also uses IMU-sensed acceleration if the Δ V accumulated over an attitude maneuver exceeds a threshold based upon known IMU errors (currently .09 fps).

Once again, the crew has limited visibility into the health of the on-board nav system. With an IMU alignment, the crew can determine if the IMU's have been drifting in attitude. Attitude errors contribute to errors in the accelerometer output, which could pollute the state vector. The crew can also compare the IMU accelerometer outputs as shown on the IMU ALIGN display. Differences between the three could indicate a problem. Currently, no independent on-board technique is available on orbit to detect state vector errors. A system using the TACAN ground stations is being developed and will be used by the on-board system to update the state vector. As of now, the crew is dependent upon the ground for state vector corrections. In OPS 2, mission control uses whole state vector updates (not deltas). Mission control also has uplink command capability to adjust the on-board nav state to compensate for Auxiliary Power Unit (APU) venting and changes in the vehicle reference area (which is used in drag computations) due to certain payload configurations. This capability has not yet been used by mission control.

25

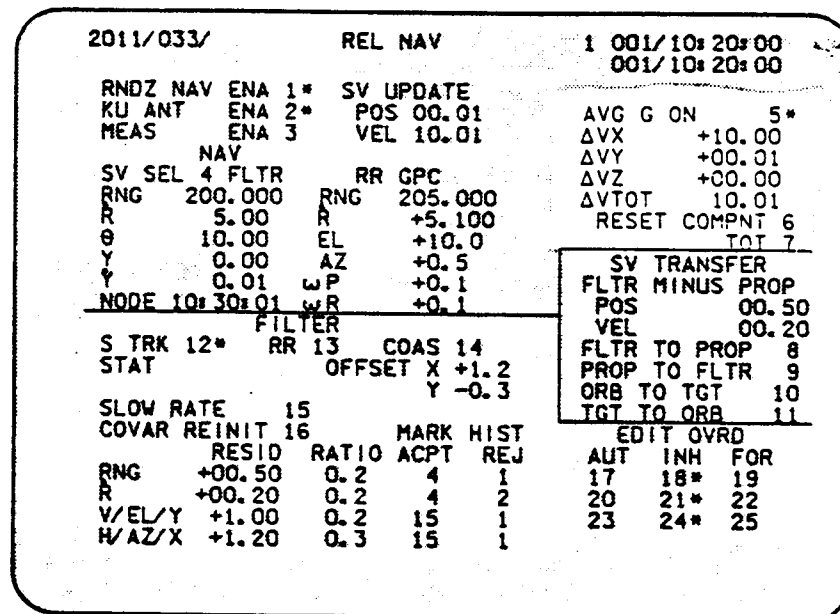


Figure 4-1. REL NAV DISPLAY - THRUST MONITOR

4.3 RENDEZVOUS NAVIGATION

Rendezvous navigation includes the software necessary to maintain an accurate estimate of both the Orbiter and target state vectors. The primary crew interface with rendezvous navigation is the REL NAV display (figure 4-2) which will be referred to throughout the following discussion. A complete description of the display can be found in section 6.

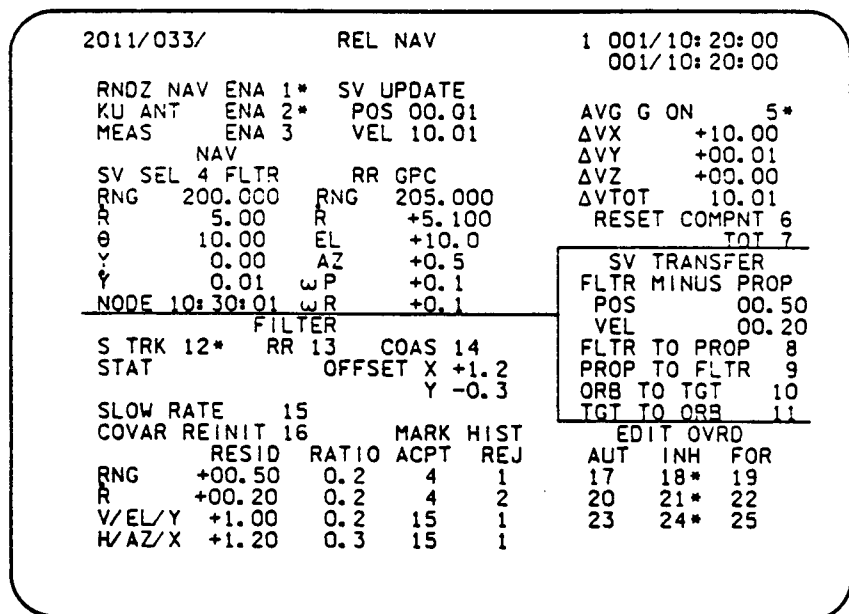


Figure 4-2. Typical REL NAV DISPLAY

Rendezvous navigation is enabled in OPS 2 by execution of Item 1 on the display. When enabled, both the Orbiter and target state vector are propagated using the Super-G algorithm. Modeled drag acceleration is used to propagate the target state vector. Modeled drag acceleration or IMU-sensed acceleration is used to propagate the Orbiter state vector based upon the same criteria as in orbit navigation (section 4.2).

External sensor data is available using the RR, ST, or COAS during rendezvous navigation. However, this sensor data is relative data; i.e., it is used by making the assumption that either the Orbiter or target state vector is "good". Preflight, it will be determined which of the two is expected to have the most stable state vector. Typically, if the target does not have translation capability, it will be considered more stable. In that case, in addition to maintaining a simple Super G propagated state vector (the PROP state vector), rendezvous navigation will also propagate a covariance matrix to be used with the incorporation of sensor data in another Orbiter state vector called the FLTR state vector. Conversely, if the Orbiter state vector was considered more stable and well known, two target state vectors would be maintained - a simple Super G propagated vector (the PROP vector) and a state vector which is updated with external sensor data (the FLTR state vector). In the future, the capability may be added to change which of the two vectors, Orbiter or target, may be updated with sensor data via a crew control. Currently, this decision must be made preflight. To simplify later discussions, it is assumed that both a "PROP" and a "FLTR" state vector will be maintained for the Orbiter.

Recall that the following data may be acquired from the external sensor data:

- The RR provides range (RNG), range rate (\dot{R}), azimuth (AZ) and elevation (EL) angles relative to the target (see section 3.2.8). Note that RR selected mode, RNG, \dot{R} , EL, AZ, pitch angle rate (ω_P), and roll angle rate (ω_R) are displayed on REL NAV.
- The ST provides horizontal (H) and vertical (V) angles to the target when in the TARGET TRACK mode (see section 3.2.6)
- The COAS provides horizontal (X) and vertical (Y) angles to the target following a crew initiated MARK. Note that navigation checks the time tag of a COAS mark and will not use the data if it is stale by over 2 minutes.

Only the RR provides range information although either the RR, ST, or COAS can provide angular data concerning the position of the Orbiter relative to the target. The crew selects the source of angular data via one of Items 12, 13, or 14 on the display. Only one can be selected. Which sensor is selected is based upon the size, brightness and range of the target. Note that, if available, RR data will be used for range and range rate regardless of whether the RR, ST, or COAS is selected for angular data.

There are cases in which rendezvous navigation will ignore external sensor data. If an acceleration greater than 20,000 μg 's is detected, the software assumes a burn is in progress and this inhibits navigation from using sensor data. The rationale for this is that erratic or incorrect sensor data could sufficiently degrade the state vector to impact burn computations. As additional protection, in Major Mode 202, (the mode in which OMS or RCS burns are made) navigation will ignore sensor data if the MEAS ENA item (ITEM 3) is deselected on REL NAV. This item is initialized disabled on transition to Major Mode 202.

In MM 201 and in MM 202 with MEAS ENA selected and no burn in progress, rendezvous navigation uses a Kalman filter to "filter" and "weight" the RR, ST, or

COAS data before incorporation in the Orbiter FLTR state vector. The rendezvous Kalman filter works similarly to the entry Kalman filter which was discussed in section 3.4.1. One difference is in the way the FORCE items work. This will be explained later. An additional difference is that the Kalman filter only updates the FLTR state vector (not the PROP state vector). The crew can monitor the effect of the sensor data on the FLTR state vector under the SV UPDATE caption on the REL NAV display. The position and velocity updates to the FLTR state vector are expressed in KFT and FPS, respectively.

The rendezvous Kalman filter works as follows: When an external sensor's data becomes available and, for angle data, the sensor is selected for use by navigation via items 12-14 on the display, the difference between navigation's estimate of the sensor's measurement and the actual measurement is computed and displayed. This is called the residual (RESID). The ratio of the residual to the maximum allowable residual at that time (computed using the covariance matrix) is also computed and displayed. The residual and ratio for RR range and range rate data are displayed next to RNG and R on the display. The residual and ratio for the sensor selected to provide angular data appear next to the V/EL/Y and H/AZ/X nomenclature on the display. This terminology comes from the ST vertical (V) and Horizontal (H) components, RR elevation (EL) and azimuth (AZ) angles and COAS X and Y components. If the EDIT OVRD function is in AUTO and the RATIO is less than one, the data is used to update the FLTR state vector. When this happens, the MARK HIST portion of the display reflects the acceptance of the data. If the RATIO is greater than one, the data would be rejected and the Reject Counter on the display increments. If the RATIO is greater than one over three consecutive times, a "!" appears on the display.

If the EDIT OVRD function is in Inhibit (INH), the associated sensor data is displayed but not incorporated in the FLTR state vector.

If FORCE is selected, the sensor data is incorporated in the FLTR state vector based upon its passing a more lenient edit test. In this test, the data passes if its ratio is less than either 1, or the sum of the last ratio value and a pre-mission-defined constant (currently this is .2). Selection of FORCE only stays in effect for one mark. The EDIT OVRD control then reverts back to the previously selected item (AUTO or INH).

The FORCE item was designed to be used with COAS data which is acquired one mark at a time. Typically, when COAS is selected as the angle data source, V/EL/Y and H/AZ/X will be placed in INH (Item 24). After a COAS mark taken with the ATT REF pushbutton is ACCEPTED on the ST/COAS CNTL display, the crewmember can view the resultant RESID and RATIO on the REL NAV display. The COAS data is then incorporated in navigation's computation of the FLTR state vector when FORCE, Item 25, is selected, assuming it passes the edit test. If this is the first time a COAS mark has been taken, the edit test involves a comparison of the RATIO with "1". As stated above, for subsequent marks, the edit test involves a comparison of the RATIO with the greater of "1" and the sum of the previous ratio and a constant (.2). Thus, the potential exists that the edit test becomes more lenient. For example, if the first mark led to a ratio of 1.5, it would not pass the edit test. If the second mark also led to a ratio of 1.5, it would pass the edit test, as this time the ratio would only have to be less than 1.7 to pass the test. The convenient aspect of placing the COAS angle

data in FORCE is that it automatically reverts back to INH after each mark is processed. This saves the crewmember the effort of resetting it back to INH between COAS marks.

Of interest is that execution of the AUTO or FORCE item for ST or RR data results in the incorporation of the next ST or RR mark if it passes the EDIT OVRD test. Execution of the AUTO or FORCE item for COAS data results in the incorporation of the currently displayed COAS mark assuming that it has passed the EDIT OVRD test and that it is not stale by over 2 minutes.

Recall that the Kalman filter is only used in computing the FLTR state vector. The PROP state vector is always available as a backup if erratic or bad sensor data manages to pass the filter and pollute the FLTR state vector. The crew can reset the FLTR state vector to the PROP state vector via item 9, PROP TO FLTR, on the display. Conversely, if it is decided that the FLTR state vector is more accurate than the PROP state vector after sensor data is processed, the PROP state vector can be updated by the FLTR state vector via item 10, FLTR TO PROP, on the display. The crew can monitor the difference between the FLTR and PROP state vectors under the FLTR MINUS PROP caption on the display (expressed in KFT and FPS). The crew controls whether the PROP or FLTR state vector is used by guidance, Universal Pointing, flight control, CRT displays and downlist with Item 4, SV SEL. One significance of this is that the selected state vector is used by the target track submode of Universal Pointing. The selected state vector is also used to compute the following parameters on REL NAV:

RNG	:	Range from Orbiter to Target (KFT)
\dot{R}	:	Range rate (fps)
θ	:	The angle between local horizontal and the projection of the Orbiter body vector selected to track the target (via UNIV PTG) into the orbit plane; i.e., the elevation angle if the Orbiter is perfectly tracking the target.
Y	:	Out of plane position (kft)
\dot{Y}	:	Out of plane velocity (fps)
NODE	:	Time of the next Orbiter/target Nodal crossing in Mission Elapsed Time (MET)

Prior to enabling rendezvous navigation, a pre-mission-determined state vector for the target is loaded in GPC memory. It is possible for the MCC to uplink a change to this initial target state vector which will then be used when rendezvous navigation is enabled. After that, the MCC can uplink a new target state vector. In addition, the crew has the capability to transfer the Orbiter state vector to the target or vice versa via ITEMS 10 and 11 on the REL NAV display. This capability could be used if the Orbiter deployed a payload, such as a balloon, and then planned to do some rendezvous/prox ops maneuvers relative to it.

The MCC also has the capability to update the FLTR state vector via uplink. They cannot update the PROP state vector (this was an oversight which eventually will be fixed). This means that the crew will have to do a FLTR to PROP state vector transfer after the ground uplinks the new FLTR state vector.

The Orbiter covariance matrix is reinitialized when a state vector update or transfer is made to the Orbiter state vector. It can also be reinitialized by the crew via ITEM 16 on REL NAV (this capability is not currently planned to be utilized). Also, when rendezvous nav is first enabled (ITEM 1), the covariance matrix is reinitialized. Portions of the covariance matrix are reinitialized when the type of sensor being used for measurement data is changed. Reinitialization of the covariance matrix results in the filter being "opened" and increased weight being given to sensor data as discussed in section 3.4.1. Also, the MARK HIST ACC/REJ counters are reset to zero. Note that changing angle source (e.g., ST to COAS) would only zero the angle MARK HIST counters. Note also that reinitialization of the Orbiter covariance matrix does not affect the target state vector.

Currently, the SLOW RATE item on the display will not be used and will have no effect on the software.

4.4 OPS 3 NAVIGATION (ENTRY AND PRE-LAND)

The navigation available during PASS OPS 3 can be subdivided into Entry navigation and pre-landing navigation. Entry navigation is used prior to MLS acquisition. During this time frame, three state vectors are propagated using Super-G based upon data from each of the IMU's. A vector selection process is then used to build a composite state vector from the three individual ones. If all three IMU's are considered good by IMU RM, a component-wise mid-value selection process is used. If only two IMU's are good, the composite state vector is the average of the two state vectors. Finally, if only one IMU passes RM, its associated state vector is used. A covariance matrix is propagated, which is used to "filter" and set "gains" for external sensor data (Drag altitude, TACAN, ADTA) which will then be used to update each of the three state vectors. Pre-land navigation, on the other hand, is used after MLS acquisition and, with it, only one state vector is propagated. A Kalman filter is used to determine incorporation of the MLS data, although the crew has no insight into this process.

In the BFS, only a single state vector is propagated, based upon the selected IMU data from IMU RM. Also, the BFS does not process MLS data.

Both delta and whole vector updates are possible during OPS 3. However, only delta state vector updates are used during atmospheric flight. As mentioned in section 3.4.2.2, the crew is required to go CSS prior to a velocity delta state update or to any kind of delta state occurring near TAEM interface to avoid excessive transient vehicle maneuvers. The MCC will ensure that an IMU alignment is accomplished close to the deorbit time and will correct the Orbiter state vector as required. As mentioned earlier, typically the MCC will not update the BFS state vector directly if it is not engaged. Instead, they will have the crew execute a PASS BFS SV XFER. This was discussed in section 3.4.2.8

During OPS 3, external sensor data will become available. See figure 4-3 for a summary of the available sensors.

Sensor	Available Beginning	Available Until
Drag Altitude	Drag Accel < 11 fps ² Altitude ≈ 240K Velocity ≈ M22	85K Altitude or ADTA H Incorporation
TACAN	Altitude ≈ 160K Velocity ≈ 8000 fps	1500' AGL Altitude or MLS Acquisition*
ADTA-H	(Deployed at M5) Velocity < M2.5**	MLS Acquisition or 1500' (STS 13 - this number changes to 500 ft.)*
MLS	Altitude ≈ 20K (R < 15 nm EL < 29° AZ < 13.5°) Runway heading and Orbiter heading within 40°	AZ and R through roll-out. EL until below 1.2° (RM uses until under .5°)

* If TACAN data is in FORCE, it is used until 1500' AGL regardless of whether MLS data is acquired. In this case, ADTA-H is used with the TACAN data.

** Not available in Mach jump region, M 1.1 < V < M 1.6

Figure 4-3. Sensor Availability During OPS 3

4.4.1 Crew Entry Nav Management. Prior to deorbit, the crew checks the HSD and verifies that the Auto/Inhibit/Force (A/I/F) items on the HSD associated with the nav sensors are properly set (figure 4-4). After the deorbit burn, the MCC will check the Orbiter state vector and make corrections, if required. If the MCC is unable to make a delta state update via uplink, they will voice-up the required change. During coasting flight, the MCC is most concerned with down-track errors which can be corrected with a Δt correction (see figure 4-5).

1: GNC DEORB MNVR COAST		2: GNC 50 HORIZ SIT	
3: BFS, GNC 50 HORIZ SIT			
HORIZ SIT CONFIG			
ALTM - ITEM 9	+	[][] . [][]	
	PASS ITEM	BFS ITEM	
PTI	INH 2 ✓	-	
INDEX	1 ✓	-	
RWY CTR	BLANK ✓	BLANK	
RWY (DEL PAD)	✓	✓	
TAEM TGT			
G&N	OVHD ✓	BLANK ✓	
HSI	BLANK ✓	BLANK	
XEP	NEP 7 ✓	NEP 7 ✓	
AIM	NOM 8 ✓	NOM 8 ✓	
TAC	INH 20 ✓	INH 20 ✓	
DRAG H	AUT 22 ✓	AUT 22 ✓	
ADTA H	INH 26 ✓	INH 26 ✓	
ADTA to G&C	INH 29 ✓	AUT 28 ✓	
DES any failed TACANS	✓	✓	
TAC	DELTA 35 ✓	-	
HUD	BLANK	-	
* C If payload undeployed: *			
* 3: GNC 53 ENTRY CONTROLS *			
* ASC FCS - ITEM 32 EXEC *			
* *			
* 3: BFS, GNC 51 OVERRIDE *			
* ASC FCS - ITEM 15 EXEC *			
* *			
* If BFS engaged: *			
* Set HSD BFS Items to PASS Config *			

Figure 4-4. Entry Checklist Pre-deorbit HORIZ SIT CONFIG

1: GNC DEORB MNVR COAST	2: GNC DEORB MNVR COAST
3: BFS, SM THERMAL	

BURN REPORT (from 3-25)

STATE VECTOR CHANGE (if reqd)

2: GNC 50 HORIZ SIT
3: BFS, GNC 50 HORIZ SIT

CRT2 ΔT - ITEM 18

CRT3 LOAD - ITEM 16 EXEC
 PASS/BFS SV XFER - ITEM 17 EXEC
 LOAD - ITEM 16 EXEC

Figure 4-5. Entry Checklist Post Burn/ Pre EI ΔT SV UPDATE PAD

Later in the entry, the crew or ground may perform a position or velocity delta state update. Figure 4-6 shows the checklist procedure for this.

$\dot{q} = 50$ RCS activity lts reconfig
 ROLL lts - 3 or 4 Yaw jets
 Pitch lts - δE rate sat
 NAV DELTA PAD

ΔX 10	()						
ΔY 11	()						
ΔZ 12	()						
ΔX 13	()						
ΔY 14	()						
ΔZ 15	()						

For Δ STATE UPDATES that include VELOCITY components (MCC call):
 P, R/Y - CSS
 DRAG A/I/F - I, then
 back to AUTO after MCC
 calls Δ STATE incorporated

Figure 4-6. Entry Checklist NAV DELTA STATE Procedure

In addition, the crew will be responsible for managing the use of drag altitude, TACAN, and ADTA in GNC.

4.4.1.1 Drag Updating. Drag altitude updating occurs during blackout at approximately $M = 22$ (240,000 feet altitude). The ground can offer no assistance in evaluating the external data or aiding the crew in deciding to allow drag to update the vehicle state. The procedure is to enter with the crew AUTO/INHIBIT/FORCE control in the AUTO mode. If the combined navigation/drag updating performance is within approximately 8σ (equivalent to approximately 80,000 ft altitude) the drag data will pass the edit criteria and will be incorporated into the nav state without incident. If the performance is worse than 8σ , editing will occur and the crew procedure will be to mode the AUTO/INHIBIT/FORCE (A/I/F) control to FORCE and incorporate the drag data even though it is outside the edit threshold (see figure 4-7).

This procedure was adopted because of a lack of discriminators available to the crew to determine the cause of the editing, plus an absolute requirement to incorporate the drag data if the navigation or update modeling is really off by more than 8σ .

1: GNC ENTRY TRAJ 1	2: BFS, GNC ENTRY TRAJ 1
3: GNC SYS SUMM 1	

(V = 24.5 - 17.0K)

$\dot{q} = 20$ Pitch jets inactive
 (ADI yaw needle now displays
 scaled A_y)

D = 11 Drag H update active

* If Drag H editing occurs: *
 * 3: GNC 50 HORIZ SIT *
 * DRAG H FOR - ITEM 24 EXEC *

Figure 4-7. Entry Checklist DRAG H Update Procedure

4.4.1.2 TACAN Updating - Initial Acquisition. The TACAN updating criteria is quite complex and may require ground/crew coordination in some cases. The rules matrix associated with TACAN data management at initial acquisition is shown as Figure 4-8. For the nominal entry, the following scenario will occur: Entry will be initiated with the rotary switch in the T/R position and channel 111 (EDW) pretuned in the thumbwheels. At about 160k ft, shortly after blackout exit, the on-board TACAN data for at least 2 Line Replaceable Units (LRU's) should be acquired and passed to the nav filter. Since the A/I/F control for TACAN will be initially in INHIBIT, the data will not be incorporated into navigation. In inhibit, the residual and ratio values do appear on the HSD if TAC azimuth or range is good. The MCC receives \approx 1.5 minutes of C-band radar skin tracking data before acquiring S-band data post blackout. Using this data, the MCC will assist the crew in evaluating the ratios prior to giving a "GO" for moding the A/I/F control to AUTO. The primary reason for asking the crew to wait for a ground "go" is to cover the unlikely case where the navigation errors and TACAN errors are compensating. This could possibly result in erroneously low ratios being observed and bad TACAN data being incorporated into navigation. It also protects the validity of the ground delta state computation in the event that a ground-initiated state vector update is required (the MCC may be computing a delta state update and errors could result if the crew incorporated TACAN data between the time that the MCC computed the uplink and the time the uplink was accomplished).

The crew should wait for communications with the ground prior to taking TACAN. However, there is a limit to how long the crew should wait before they decide to take steps to troubleshoot the lack of good TACAN data independently. This limit has been established as $V_{REL} = 6000$ fps. This was chosen because it is associated with a nominal Acquisition Of Signal (AOS) plus approximately two minutes and because the Orbiter ranging potential is shrinking to the point that it is becoming more and more urgent to correct the vehicle state.

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B. NAV FILTER MANAGEMENT FOR TACAN/BARO/DAG AUTO/INHIBIT/FORCE

1. TACAN - INITIAL PROCESSING (INITIALLY IN INHIBIT)

NOTE: TACAN DATA WILL NOT BE INCORPORATED IN THE BFS PREENGAGE. VECTOR TRANSFER FROM THE PASS IS REQUIRED WHEN BFS ERRORS EXCEED Δ STATE MANAGEMENT LIMITS.

		RATIO > 1		
	RATIO < 1	BAD TACAN	BAD STATE	1-LOCK
PRE-COMM (ASSUME NO COMM IF $V_{REL} < 6000^*$ FPS, NOM AOS +2 MIN, H = 130K FT)	REMAIN IN INHIBIT	REMAIN IN INHIBIT	REMAIN IN INHIBIT	REMAIN IN INHIBIT
COMM	GROUND CALL; AUTO***	GROUND CALL; INHIBIT	GROUND CALL; FORCE	GROUND CALL; PRIME SELECT DESELECT MISSING TACAN's
NO COMM	AUTO	FOLLOWED BY Δ STATE UPDATE	(RETURN TO AUTO WHEN RATIO < 1)	(RESELECT NON-FAILED TACAN LRU's WHEN 2 LOCK
		TROUBLESHOOT TO DETERMINE CAUSE OF EDITING A. SWITCH GROUND STATIONS B. CHECK IMU STATUS C. OBSERVE RESIDUAL, RATIO BEHAVIOR D. MONITOR WITH HSI		WAIT UNTIL $V_{REL} < 5500^{**}$ FPS THEN PRIME SELECT DESELECT MISSING TACAN's
		AUTO	FORCE	(DO NOT FORCE)

*FOR RTLS, $V_{REL} < 6500$ FPS. **FOR RTLS, $V_{REL} < 4700$ FPS.
***EVEN THOUGH THE RATIO IS < 1, TACAN DATA WILL NOT BE ACCEPTED IF THE GROUND RADAR INDICATES THAT INCORPORATION OF THE DATA WILL DEGRADE THE NAV STATE.

Figure 4-8. INITIAL TACAN PROCESSING FLIGHT RULES

Once communication with the ground is established, one of two failures can cause the TACAN ratios to be greater than one. The fault could lie with the TACAN data or with the on-board vehicle state. If the ground determines that the TACAN data is bad by comparing the TACAN residuals with the on-board state and the radar ground filter state, the recommendation will be to try a new ground station. If the original ground station was providing erroneous data, this will solve the problem. If the on-board LRU's were performing improperly, switching ground stations will not be a solution. In this case, the crew should remain in INHIBIT, and a delta state command uplink will have to be performed when/if the errors exceed the following tolerances:

- A. $H > 130K$ ft
 - X/Y components $> 48K$ ft
 - Z component $> 12K$ ft
- B. AT $H < 130K$ ft
 - X/Y components $> 6K$ ft
 - Z components $> 3K$ ft
- C. X/Y/Z components > 75 ft/sec (high speed filter velocity components).

If the ground determines that the vehicle state is erroneous, the proper procedure to recommend to the crew is to mode the A/I/F control to FORCE. This will allow the data to be incorporated into navigation even though the vehicle estimates that the data should be edited.

The only other case to be covered when the ground has communications involves only one LRU locking onto a TACAN ground station at initial acquisition. At initial acquisition, the on-board RM must have two LRU's locked on before it will pass the data to the navigation filter. If for any reason the vehicle only locks up with one LRU and the crew and ground can verify that the data is really good, the proper procedure is to incorporate that data into navigation rather than perform a delta state update. The only way to incorporate that data into navigation is to artificially remove the 2-lock requirement from RM. This is done by deselecting the two LRU's which have not locked on. The RM then thinks that only one good LRU remains and overrides the 2-lock requirement. The point in the trajectory when this procedure will be done is a function of the navigation errors present, i.e., if the errors are small, additional time may be allowed for the RM 2-lock requirement to be met.

In the NO-COMM case, the crew must make decisions in the operation of the A/I/F controls independently from the ground. The NO-COMM case may be assumed to exist by the crewmembers if they are entering to a contingency landing site and know that no communications with the ground are possible, or if they are entering to a site where communications should be available but have not established communications by $V_{REL} = 6000$ fps (NOM AOS + 2 min). If the ratios are less than 1, the crew should select AUTO and allow the data to be incorporated by navigation.

If the ratio is greater than one, the crew must use the on-board indication to decide whether the TACAN data is bad or if the vehicle state vector is bad. The following procedures are available to the crew:

- A. Switch ground stations. This is done by switching the TACAN from T/R to GPC. If the new ratios come up greater than one it probably indicates a bad nav state, although there may be a small probability that the problem is really in the on-board TACAN LRU's.
- B. Check IMU status. If the IMU mission performance has been nominal, and a recent IMU alignment has occurred, and no IMU failures have been declared during the entry, it is unlikely that the on-board nav state could be in error by a sufficient magnitude to cause ratios greater than one. Therefore, the crew should suspect TACAN errors. Alternatively, if the IMU's have been a source of continuing problems during the mission, or if an IMU alignment was not performed shortly before entry, or if an IMU has been declared failed during entry, the crew should suspect that the nav state is in error.
- C. Observe residual, ratio behavior. If the values of the residuals/ratios are steady or show a constant trend, it is likely that the nav state is the source of error; however, if the values of the residuals/ratios are erratic, it is likely that the TACAN data is erroneous.
- D. Monitor with HSI - This is another cumbersome procedure that theoretically allows the crew to gain some insight into the validity of the TACAN data. The crew can select raw TACAN data to drive the HSI and compare the range and bearing to the TACAN station with the navigated position and a visual estimate of the position. This will be a difficult procedure for the crew because the values on the Horizontal Situation Indicator (HSI) will be continually changing. As the magnitude of the errors would have to be quite large to be detected with this technique, the crew probably would have already decided the error source by one of the other methods before trying this technique.

By one or more of the above procedures, the crew should be able to discriminate independently between bad TACAN data and a bad state vector. If it is determined that the TACAN data is in error, the crew should mode the A/I/F control to AUTO and attempt to select another ground station.

If it is determined that the state vector is in error and the TACAN data is valid, the crew should mode the A/I/F control to FORCE. This will cause the TACAN to be incorporated into navigation.

The only other possible problem situation with NO COMM is the case where only one LRU locks onto the TACAN station. In this case, the crew should wait as long as it can to allow the auto antenna and station selection to work properly. At approximately $M = 5.5$ they should deselect the two TACAN LRU's that have not locked up and attempt to incorporate the TACAN data from the LRU that has locked on. It has been decided that the crew should also switch the A/I/F control to AUTO in this case and should not force the data into nav.

FLIGHT RULES

4.4.1.3 TACAN Updating - Post Convergence. The flight rule matrix associated with TACAN data management after the on-board nav filter has processed some TACAN data is shown on figure 4-9. For the nominal entry, the crew will leave the TACAN's in AUTO and the TACAN data will continue to be processed. The ratio should never grow greater than one during a nominal case.

If, for any reason, the ratio does become greater than one after the Orbiter has processed some TACAN data, the ground or crew can utilize the same techniques as were used at initial acquisition to determine if the cause is bad TACAN data or if it is a bad state vector. In the event that the problem is bad TACAN, the actions are the same as at initial acquisition. The procedures change, however, if the problem is a bad state vector. In the initial acquisition case the action was to force the TACAN data into nav. In the post-convergence case, processing previous TACAN data will have already converged the covariance matrix, and even forcing the data will probably not have the desired effect. That is, the covariance matrix will downweight the TACAN data to the extent that the state vector will not be corrected even if the A/I/F control is changed to FORCE. The procedure to use in this case (either with or without comm) is to first perform a zero delta state vector update to reinitialize the covariance matrix, and then force the data.

The 1-lock column is deleted from the post-convergence matrix because the on-board RM ceases to inhibit single TACAN data from being incorporated into navigation after only a few TACAN measurements have been incorporated. This means that after convergence, the two lock requirement is removed.

Figure 4-10 shows the abbreviated format of the Flight Rules Matrices, which are part of the on-board checklist.

In order to provide protection for the case in which bad sensor data passes the filter and pollutes both the PASS and BFS state vectors, TACAN data will not be incorporated in the BFS pre-engage. A state vector transfer from the PASS will be requested when the BFS exceeds the allowable errors.

ITEM

4-73
(Cont)

2. TACAN - POST CONVERGENCE (INITIALLY IN AUTO)

	RATIO <1	RATIO >1	
		BAD TACAN	BAD STATE VECTOR
COMM	REMAIN IN AUTO	GROUND CALL; INHIBIT FOLLOWED BY A STATE UPDATE IF RQ'D. (BACK TO AUTO WHEN RATIO <1)	REMAIN IN AUTO PERFORM A ZERO A STATE UPDATE IF RATIO STILL >1; FORCE
NO COMM	REMAIN IN AUTO	TROUBLESHOOT TO DETERMINE CAUSE OF EDITING	
		REMAIN IN AUTO	REMAIN IN AUTO PERFORM A ZERO A STATE UPDATE, IF RATIO STILL >1; FORCE

THIS RULE IS CONTINUED ON THE NEXT PAGE

MISSION	REV	DATE	SECTION	GROUP	PAGE NO.
ALL		10/12/82	4 TRAJ, GUID	ENTRY	4-25

7001

Figure 4-9. POST-CONVERGENCE TACAN FLIGHT RULES

NASA-JSC

1: GNC ENTRY TRAJ 4	2: BFS, GNC ENTRY TRAJ 4
3: GNC 50 HORIZ SIT (V = 10.5 - 6.0K)	

V = 8K √Aileron trim. If > 2.0, anticipate Lat/Dir problems through M = 2

TACAN MGMT

	RATIO < 1	RATIO > 1	ONE TACAN LOCKED	NO LOCK
PRE-COMM	INH	INH	INH	INH
COMM OK	MCC: AUTO or INH (if TACAN will degrade NAV state)	MCC: INH (+Δ STATE) or FORCE or ZERO Δ STATE or CHG TACAN CH	MCC: DESELECT MISSING TACAN(S) then - AUTO	MCC: TACAN MODE (three) - GPC

V = 6K **NO COMM TACAN MGMT**

	RATIO < 1	RATIO > 1		ONE TACAN LOCKED	NO LOCK
		TROUBLESHOOT		BELOW V = 5.5K	BELOW V = 5.5K
		IF BAD TACAN	IF BAD NAV STATE	DESELECT MISSING TACANS, then -	TAC (three) - GPC
	AUTO	AUTO	IF 1st acq-FORCE IF NOT - ZERO Δ STATE	AUTO	

Roll reversals below M = 8 may be in CSS at Crew option

Figure 4-10. Entry Checklist TACAN MANAGEMENT PROCEDURE

4.4.1.4 ADTA Management. Procedures for barometric (ADTA) altitude updating in navigation are shown in figure 4-11 from the Flight Rules document. This procedure was written assuming the ADTA-H A/I/F control is in INHIBIT initially. The ADTA probes are deployed by the crew at M = 5. At this time, the crew can compare the data from the left and right air data probes with the nav estimate of the data on the dedicated displays (AMI, AVVI). The crew can also compare the individual ADTA's data on the PASS OVERRIDE display. With ADTA-H in INHIBIT, the crew also can monitor the current residual and ratio on the HSD. ADTA data is available into navigation from M = 2.5, except for an area near M=1 where unstable air flow is expected. This is called the Mach jump region and extends from M = 1.6 to M = 1.1.

The nominal procedure with ground communications is for the crew and ground to evaluate the baro data. If the ratio is less than 1, and ground radar indicates that incorporation of the ADTA data will not degrade the nav state, the crew will be asked to mode the A/I/F control to AUTO. This will initiate processing of baro altitude data into navigation beginning just after M = 2.5.

If the data indicates a ratio greater than 1 and communications with the ground exists, the ground will be able to isolate the cause as being either a bad state vector or bad baro data by using the ground radar as the independent vote. If the baro data is bad, the ground call will be for the crew to leave the A/I/F control in INHIBIT. This will prevent the already adequate on-board Nav state from being polluted by bad baro altitude data. If the on-board state vector is bad, the ground call will be to mode the A/I/F control to FORCE. This will allow the bad state to be updated by the good baro data. If the ratio subsequently becomes less than 1, the crew will change the A/I/F control to AUTO to allow editing of possible invalid data points.

If the data is not passing RM, i.e., is not even being made available for navigation to edit, the ground will assist the crew in deselecting ADTA's such that only one will be prime selected.

For the NO-COMM case with the ratio < 1, the crew will go to AUTO.

For the NO-COMM case with the ratio > 1, the crew has very little on-board information available to help decide whether the baro is bad or the nav state is bad. Current procedures are for the crew to remain in INHIBIT if valid TACAN data is being processed. If TACAN data is not being processed, the requirement for baro altitude into navigation is even stronger. The only method of crew evaluation is to monitor the HSD residuals. If the ADTA data appears steady and reasonable considering the past navigation performance, the crew should mode the A/I/F control to FORCE. If the residuals are erratic or unreasonable based on past navigation system performance, the crew should mode the A/I/F control to AUTO to allow the data to be processed if it becomes valid.

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R ITEM

4-73 (Cont)	3. BARO (INITIALLY INHIBIT)			
	RATIO <1	RATIO >1		NOT PASSING RM
		BAD BARO	BAD STATE VECTOR	
COMM	GROUND CALL: AUTO ①	GROUND CALL: REMAIN IN INHIBIT	GROUND CALL: FORCE	GROUND CALL: PRIME SELECT
NO COMM	AUTO	TACAN OK: REMAIN IN INHIBIT NO TACAN: IF RATIO STEADY, FORCE IF RATIO ERRATIC, AUTO		WAIT UNTIL M < .9, THEN PRIME SELECT (DO NOT FORCE)

① EVEN THOUGH THE RATIO IS <1, BARO DATA WILL NOT BE ACCEPTED IF THE GROUND RADAR INDICATES THAT INCORPORATION OF THE DATA WILL DEGRADE THE NAV STATE.

The only other possible situation is NO COMM along with the data not passing RM. In this case, the crew should wait until $M < 1.1$ then deselect ADTA's until only one remains. They should then mode the A/I/F control to AUTO and let the data be edited if the ratio is still greater than 1. If the data is not acceptable at this point, it has been decided that the probabilities are that the ADTA data is in error rather than the state vector, and forcing would be the wrong solution.

As discussed in section 3.2.4, ADTA data can also be used by guidance, flight control, and the AMI/AVVI dedicated displays as controlled by the crew via the ADTA to G&C A/I/F items on the HSD. In order for G&C to use ADTA data, the following three conditions must be met: the velocity must be less than M 2.5, an air data probe is deployed, and no air data dilemma exists. The checklist has the crew place ADTA TO G&C in AUTO on the HSD if there are at least two good ADTA's, air data altitude, α , and M look reasonable and, if there is communication with MCC, the MCC has given a "go". Note that if only one ADTA is available, the crew should leave ADTA to G&C in INH and place P and R/Y in CSS. In addition, if ADTA to G&C is not incorporated prior to M 2.5, the crew is required to go PITCH - CSS prior to its incorporation to avoid flight control transients. Recall that while navigation uses only air data altitude, guidance and flight control need the other air data parameters (α , M, \bar{q} , EAS) to be able to function correctly. The flight control system is very sensitive to α errors and to \bar{q} errors which are induced by α errors. As discussed in section 3.2.4, if air data is not incorporated by G&C, flight control will use NAVDAD parameters down to M 1.5. Errors are induced as navigation cannot account for winds or gusts. At M 1.5, the possible wind-induced errors due to NAVDAD α are too large for flight control, so "default air data" begins being used. Default air data assumes α remains a constant 7.5° and \bar{q} is a canned function of VREL. Note that the dedicated and CRT displays still show the NAVDAD computation for \bar{q} , α and EAS. When default air data is used, the crew should take manual control of the vehicle (P and R/Y-CSS, Speedbrake - MANUAL) and fly pitch attitude based upon the θ limits displayed on the VERT SIT 1 and 2 displays. See figure 4-12.

Of interest is that if the ADTA's go into a dilemma while in FORCE or AUTO, NAVDAD or default air data will be sent to G&C (NAVDAD if $VREL > M1.5$, default air data if $VREL < M1.5$).

Air data altitude (ADTA-H) is left in INHIBIT in the BFS pre-engage. This way, BFS navigation cannot be polluted by erroneous ADTA data. If the BFS nav state exceeds error tolerances, a PASS to BFS state vector transfer will be made by the crew based upon a ground call. The BFS ADTA to G&C item is placed in AUTO for entry. This is required in case the crew must quickly downmode to BFS. In such a case, air data would immediately be available for flight control. In BFS, only NAVDAD is available if ADTA data is not incorporated in G&C - no default air data is computed.

Figure 4-11. ADTA-H (BARO) FLIGHT RULES

ADTA MGMT					
NAV					G&C
RATIO < 1		RATIO > 1			Two or more good ADTAs
		IF BAD ADTA	IF BAD NAV STATE		
COMM OK	MCC: AUTO or INH*	MCC: INH	MCC: FORCE		Evaluate h,α,M MCC: AUTO (G&C)
NO COMM	AUTO	NO TACAN			Evaluate h,α,M If reasonable: AUTO (G&C)
		TACAN OK	ADTA ERRATIC	ADTA STEADY	
		INH	AUTO	FORCE	

*(If ADTA H will degrade NAV state)

Figure 4-12. Entry Checklist ADTA MGMT Cue Card

4.4.1.5 MICROWAVE SCANNING BEAM LANDING SYSTEM (MLS). There are really no procedures or rules for MLS data incorporation. No controls are available to the crew to inhibit or force MLS data. The auto edit threshold will be set at 8σ , so the probability of editing will be very remote. Should editing occur, however, the crew will merely ignore the Nav Edit alarm and continue the landing in CSS. The ground will assist the crew by monitoring the MLS residuals and ratios, and will advise them of the cause for the editing.

When MLS data is acquired, the TAC and ADTA H ratios and residuals blank. Also, the " | " by MLS on the GNC SYS SUMM display will disappear. The only crew interaction with the MLS is to ensure that the MLS's are powered on, that no commfault exists (I/O RESET if necessary) and the proper channel for the landing site is selected.

4.5 RTLS NAVIGATION

RTLS navigation works similarly to Ascent and Entry navigation with the following exceptions:

- Single state navigation is used throughout the Return To Launch Site Abort (RTLS)
- The MCC will update the state vector with delta state vector updates only
- The MCC will do delta state updates to maintain the state vector more stringently in an RTLS than a nominal entry
- TACAN is usually acquired by 220K. TACAN management is similar to entry. See figure 4-13.
- ADTA's are handled as in entry
- The MLS is powered off for ascent. Thus, the crew will be required to power on the MLS at $\approx 85K$ and do an I/O RESET to clear the MLS comm-fault.

BFS navigation during an RTLS is similar to the PASS. MLS data, however, is not used. Also, the pre-engage BFS state vector is updated via a PASS to BFS SV XFER instead of a delta state update from the ground.

1: GNC VERT SIT 1		2: GNC SYS SUMM 1	
3: BFS, GNC VERT SIT 1			
α RECOVERY PHASE			
Monitor α recovery (α = 50° until -1.8g maintain 2.2g)			
h = 220 K	TACAN AOS		
OME = 235 NM	BFC CRT DISP - OFF		
3: GNC 50 HORIZ SIT			
TACAN MGMT			
RATIO <1	RATIO >1	ONE TACAN LOCKED	NO LOCK
MCC: AUTO or INH (if TACAN will degrade NAV state)	MCC: INH (+Δ STATE) or FORCE or ZERO Δ STATE or CHG TACAN CH	MCC: DESELECT MISSING TACAN(S) then - AUTO	MCC: TACAN CH (three) - 097X TACAN MODE (three) - T/R

1: GNC VERT SIT 1		2: GNC SYS SUMM 1	
3: GNC 50 HORIZ SIT			
Nz Overbright Nz HOLD PHASE (1.8g's)			
Nz constant at 2.2g's			
h = 110K NO COMM TACAN MGMT			
* RATIO <1	RATIO >1	ONE TACAN LOCKED	NO LOCK
* * * * *	TROUBLESHOOT	BELOW V = 4.7K	BELOW V = 4.7K
* * * * *	IF BAD TACAN	DESELECT MISSING TACANS, then -	TACAN CH (three) - 097X TACAN MODE (three) T/R
* * * * *	IF BAD NAV STATE	AUTO	
* * * * *	AUTO	If 1st acq-FORCE	
* * * * *		IF NOT - ZERO Δ STATE	

Figure 4-13. ASCENT CHECKLIST RTLS TACAN MANAGEMENT

SECTION 5

LANDING SITE UPDATE

Space Shuttle missions require the capability to land at a variety of locations. In addition to the landing site designed for a nominal End-Of-Mission (EOM), there must also be landing sites for Abort Once Around (AOA), Transatlantic Abort Landings (TAL), Return to Launch Site (RTLS), and contingency landings required for an emergency deorbit. For example, the following landing sites and specific runway numbers were designated for STS 6.

Nominal EOM and AOA:	Edwards Air Force Base, California EDW 22 EDW 17
Backup AOA:	Northrup Strip, New Mexico NOR 17 NOR 35
RTLS:	Kennedy Space Center, Florida KSC 15 KSC 33
TAL:	DAKAR Naval Station, SENEGAL YOF 01 YOF 19
Contingency Landing:	All runways above, plus Hickam Air Force Base, Hawaii HNL 08 HNL 26
	Kadena Air Base, Okinawa, Japan KAD 05 KAD 23
	Edwards Air Force Base, California EDW 04 EDW 15
	Northrup Strip, New Mexico NOR 05 NOR 23
	Rota Naval Station, Spain AOG 10 AOG 28

The process of selecting a runway and the associated TACAN and MLS data is part of the landing site update function - a subfunction of navigation.

5.1 PASS LANDING SITE UPDATE

The data necessary to support a landing at each of the above runways is loaded in the mass memory preflight in what is called the maxitable. This table can contain up to 20 runways and 60 different TACAN stations. The maxitable is subdivided into separate data sets called minitables. Only one minitable is available for use during OPS 3 or 6. It contains a list of three runways which can be viewed by the crew on the HORIZ SIT display (figure 5-1). The runways are designated PRIMARY, SECONDARY and ALTERNATE. In OPS 3 or 6, the crew has the freedom of selecting one of these three runways as the landing site. The minitable also contains data concerning the three runways, data for ten TACAN stations and MLS (also known as MSBLS) data for the primary and secondary runway if available. The arrangement of data in the minitable is shown below:

Runway data for:

- Primary Runway
- Secondary Runway
- Alternate Runway

MLS data for:

- Primary Runway (if it has MLS)
- Secondary Runway (if it has MLS)

TACAN data for ten stations.

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Runway data includes the following: runway name, geodetic latitude, longitude, azimuth, altitude of runway above reference ellipsoid, altitude of reference ellipsoid above Mean Sea Level (MSL), magnetic variation, and MLS available flag.

MLS data includes: geodetic latitude, longitude, altitude and X-component in runway coordinates for the elevation antenna; geodetic latitude, longitude, altitude, and X and Y-components in runway coordinates for the range/azimuth antenna; elevation boresight; azimuth boresight relative to true north; and range, elevation, and azimuth bias.

TACAN data includes: TACAN channel number, geodetic latitude, longitude, altitude of station above reference ellipsoid, altitude of ellipsoid above mean sea level, magnetic variation, and bearing and range bias. (Bias values are currently constrained to zero.)

3041/050/		HORIZ SIT					005/01:50:00 000/00:20:00		
PTI	INM2	ALTM					NAV DELTA		
INDEX		9 29.92					Δ X 10		
							□		
RWY CTR	L						Δ Y 11		
EDW22	3*						□		
EDW17	4						Δ Y 12		
NOR17	5						□		
							Δ Y 13		
TAEM TGT							□		
G&N OVHD	6						Δ Y 14		
HSI							□		
XEP							Δ Y 15		
AIM NOM	8						□		
							LOAD 16		
							18 Δ T □		
NAV TAC	AZ	RESID	RATIO	AUT	INM	FOR	TAC111	TAC2111	TAC3111
	RNG	+ 1.2	0.1	19*	20	21	+ 1.3	+ 1.2	+ 1.1
		+110.5	0.1				+110.4	+110.6	+110.3
DRAG	H	+500	0.1	22*	23	24	DES 31	DES 32	DES 33
ADTA	H			25	26*	27	HUD37L	ABS	34
				28	29*	30	38R	DELTA	35*

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Figure 5-1. HORIZ SIT DISPLAY - Runway Designation

Which of the available minitables is used in OPS 3 or 6 depends upon the sequence of OPS transitions which have occurred or upon crew changes to the Landing Site Update function on the UNIV PTG display in OPS 2. In OPS 1, the RTLS minitable is loaded. If an RTLS is selected, the RTLS minitable is immediately available. Note that the RTLS minitable has one runway and two TACAN's at the TAL landing site (for STS 6, DAKAR, SENEGAL). Thus the capability to perform the manual contingency TAL procedure (used when a transition to OPS 3 cannot be done such as when 3 main engines fail) is preserved. The AOA minitable is loaded when the GPC's are transitioned directly from OPS 1 to OPS 3 unless a TAL has been selected before Main Engine Cut Off (MECO). In this case, the TAL runways overwrite the AOA runways although the selected TACAN stations remain unchanged. The AOA minitable is designed, then, to provide TACAN coverage for either AOA or TAL. In the nominal case, when the GPC's are transitioned to OPS 2, the nominal EOM minitable is loaded. While in OPS 2, the crew has the capability to select a different minitable using the landing site update capability (discussed later). Whichever minitable is selected in OPS 2 (nominal EOM or contingency) is then carried over to OPS 3. A transition from OPS 3 back to OPS 2 will reinitialize the selected runway to the nominal EOM table.

Figure 5-2 shows the available STS 6 minitables.

In OPS 2, the crew can create a contingency minitable, if necessary, with items 25, 26, and 27 on the UNIV PTG display (figure 5-3). These items allow input of the primary, secondary and alternate runways identifiers found in the OPS 2 maxitable. The identifiers which can be entered by the crew range from 1 to 18. In figure 5-2, these numbers are listed under the CONT X runway name. For example, runway identifier 4 goes with KSC 15, identifier 16 goes with NOR 35. The nominal EOM runways and the associated minitable are specified with items 19, 20, and 21. These identifiers cannot be re-input to the UNIV PTG display once changed. They can only be reinitialized back to the initial values of 19, 20, 21 upon transition OPS 2 - 3 - 2. However, the nominal EOM minitable can usually be created by the appropriate selection of PRI, SEC and ALT runways.

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	EOM 19, 20, 21	RTLS	AOA	TAL	OPS 2 MAXI TABLE				
					CONT 1 EDM 1, 2, 3	CONT 2 KSC 4, 5, 6	CONT 3 KAD/MHL 7, 8, 9, 10	CONT 4 SPAIN/EDM 11, 12, 13, 14	CONT 5 NOR 15, 16, 17, 18
Rw-PRI Rw-SEC Rw-ALT	EDM 22 EDM 17 NOR 17	KSC 15 KSC 33 YOF 01	EDM 22 EDM 17 NOR 17	YOF 01 YOF 19 AOG 26	EDM 22 NOR 17 EDM 23	KSC 15 KSC 33 YOF 01	KAD 05 KAD 23 MHL 08 MHL 26	AOG 10 AOG 28 EDM 15 EDM 24	YOF 19 NOR 35 NOR 23 NOR 05
MLS PRI MLS SEC	8 6	8 6	8 6	NO MLS	8 8	8 6	NO MLS	NO MLS	NO MLS
T R	TAC 1 TAC 2 TAC 3	EDM 111 SNG 69	COF 97 YF 78 (DME ONLY) YOF 68	YOF 68 EDM 111 EDM 111 SNG 69	EDM 111 SNG 69	TTS 594 YF 78	KAD 57 MHL 100	AOG 23	SNG 69 YOF 68
G P C	TAC 4 TAC 5	PMD 92	TTS 594 YF 78 PMD 92 AOG 23	YF 78 PMD 92 AOG 23	PMD 92	COF 97	LTC 98 DKH 86	GBA 53	MOM 92 YF 78

Figure 5-2. STS 6 Landing Site Data Chart

```

2011/ / UNIV PTG 1 002/10:15:00
CUR MNVR COMPL 10:20:00 002/10:15:00
1 START TIME 002/10:10:00

MNVR OPTION START MNVR 18*
5 R 110.3 TRK 19
6 P 201.1 ROT 20
7 Y 005.2 STOP 21

TRK/ROT OPTIONS ATT MON
8 TGT ID 2 22 MON AXIS 1 +X
ERR TOT 23*
ERR DAP 24

9 RA 000.000
10 DEC 000.000
11 LAT 000.000
12 LONG 000.000
13 ALT 000.000

CUR ROLL PITCH YAW
REOD 110.30 205.10 020.00
ERR +000.50 -006.00 +15.00
RATE +00.2 -00.2 +03.000

14 BODY VECT 1

15 P 000.00
16 Y 000.00
17 OM 000.00

LDG SITE UPDATE
25 PRI 19 EDW22
26 SEC 20 EDW17
27 ALT 21 NOR17

```

Figure 5-3. UNIV PTG Display - LDG SITE UPDATE

To aid the crew in loading a contingency minitable in OPS 2, the Deorbit Prep Checklist contains a Landing Site Data Chart (figure 5-4).

Updating the primary runway in the minitable with a runway from the maxitable does three things:

1. Runway data for the new runway is transferred to the minitable
2. If the runway has MLS data, then the data is transferred
3. TACAN station data is transferred for the set of TACAN's in the column below the selected runway.

Updating the secondary runway in the minitable does two things:

1. Runway data for the new runway is transferred to the minitable
2. If the runway has MLS data, then the data is transferred.

Updating the alternate runway in the minitable transfers only runway data.

It is important to note that the choice of the primary runway completely controls the selection of TACAN stations for the minitable. Since the minitable holds three runways but only one set of ten TACAN stations, the runways should be from the same geographic area to provide TACAN coverage. The maxitable has the runways arranged in columns by geographic area for this purpose. In the case of CONT minitables 3 and 4, in figure 5-4, there are runways from two different geographic areas grouped together.

40 Notice that the CONT 3 minitable includes TACAN's for Kadena and for Hawaii. Selection of any runway in that column as the primary runway will result in all TACAN's in that column being transferred to the minitable. In the CONT 4 minitable, two contingency runways at Edwards AFB are grouped with the runways at Rota, Spain; however, the TACAN's are for Rota.

It also would be possible for the MCC to uplink changes to the OPS 2 maxitable, although this capability is usually limited to replacing failed TACAN ground stations or inputting data for a contingency landing runway not already contained in the on-board tables. A transition from OPS 2 to OPS 8 and back to OPS 2 does not affect any changes made to the Mini/Maxi tables. On the other hand, a transition from OPS 2 to OPS 3 and back to OPS 2 retrieves the original maxitable and clears any uplinked changes. The MCC can also uplink changes to the minitable in OPS 3.

OPS 2 MINI TABLE		OPS 2 MAXI TABLES				
	EDM	CONT 1	CONT 2	CONT 3	CONT 4	CONT 5
	19, 20, 21	EDM 1, 2, 3	KSC 4, 5, 6	KAD/HNL 7, 8, 9, 10	SPAIN/EDW 11, 12, 13, 14	NOR 15, 16, 17, 18
RW-PRI	EDW 22	EDW 22	KSC 15	KAD 05	AOG 10	YOF 19
RW-SEC	EDW 17	NOR 17	KSC 33	KAD 23	AOG 28	NOR 35
RW-A'Y	NOR 17	EDW 23	YOF 01	HNL 08	EDW 15	NOR 23
				HNL 26	EDW 04	NOR 05
MLS-PRI	8	8	8	NO	NO	NO
MLS-SEC	6	8	6	NO	NO	NO
TAC 1	EDW 111	EDW 111	YTS 59Y	KAD 57	AOG 23	SNG 69
TAC 2	SNG 69	SNG 69	YF 78	HNL 100		YOF 68
TAC 3			YOF 68			
TAC 4	PHO 92	PHO 92	COF 97	LYC 98	GBR 83	HAW 92
TAC 5				CKH 86		YF 78

NOTES:

1. Landing site updates are made to PASS by Items 25, 26, & 27 (OPS 2) GNC UNIV PTG display and BFS by Items 6, 7 & 8 (OPS 3) GNC 51 OVERRIDE display
2. Minitable runways cannot be entered on the PASS display by ITEM entry.
3. If no changes are made in OPS 2, the Minitable EDM sites are automatically loaded; BFS EDM should match.
4. The TACANs for the landing site are established by Item 25 (ITEM 6, BFS) PRI RWY. If you choose a PRI RWY from the Maxitable, the TACANs listed in that column will be loaded.
5. MLS is supported only in the PASS for the PRI and SEC slots and cannot be uplinked. If an Item 25 or 26 PRI/SEC RWY is selected from the Maxitable, the associated MMLS coordinates (if any) will be loaded.

Figure 5-4. STS 6 Landing Site Data Chart - D/O PREP Checklist

Any TACAN station in the minitable can be used if it is manually selected with the TACAN thumbwheels while in the T/R mode. Typically, the TACAN selected via T/R is the prime TACAN for a landing site. Only TACAN stations in slots 4 through 9 can be used by the automatic logic in the GPC mode. On the D/O PREP C/L Landing Site Data Chart, the TACAN's that will be used if GPC is selected are indicated by the "GPC" annotation. This feature can be used in case of a TACAN ground station problem. There are several items of interest regarding the TACAN station listings. TTS 59Y is the prime TACAN ground station at KSC. A TACAN station with a "Y" in its identifier will appear as "-59" on the HORIZ SIT display. All of the other TACAN stations in the tables have no minus sign, so their ID numbers are followed by an X. For example, the mobile station at Northrup is listed as SNG 69 which means that its ID number is dialed in as "069 X," and on the HORIZ SIT display it would appear as "069." Another point of interest is that the Dakar Station YF 78 is only a DME, i.e., only range information can be acquired instead of both range and bearing.

5.2 BFS LANDING SITE UPDATE

The BFS landing site update capability is somewhat different than in the PASS. The contents of the maxitable for the BFS are the same as in the PASS with the exception that no MLS data is included. However, as all BFS OPS are loaded pre-flight in the BFS GPC, all of the maxitable data is resident in the BFS throughout the flight. The crew capability to select a contingency minitable is available in OPS 3 via the BFS OVERRIDE display (figure 5-5). This functions as in the PASS. The crew can only enter runway numbers 1-18 to the display, although the nominal EOM runways will appear with identifiers 19, 20, 21, the AOA runways will have identifiers 22, 23, 24, and the TAL runways will have identifiers 25, 26, 27. As in the PASS, the crew can select Primary (PRI), Secondary (SEC), and Alternate (ALT) landing sites from the selected minitable via the BFS HORIZ SIT display (figure 5-6). Pre-engage, however, the BFS "listens" to changes to the PASS HORIZ SIT display via ITEMS 3, 4 and 5 and thus will automatically stay consistent with the PASS. Note that if the PASS minitable is modified by the crew via landing site update in OPS 2, the crew will need to repeat the procedure for the BFS after the BFS OPS 3 transition.

As with the PASS, a specified minitable is loaded in the BFS following certain OPS transitions. Initially in OPS 1, the RTLS minitable is loaded. A transition from OPS 000 to Major Mode 301 results in the nominal EOM table. A transition from Major Mode 105 or 106 to 301 results in the AOA table. A transition from 104 (i.e., pre ET SEP) to 301 results in the TAL table.

Also, as in the PASS, selection of a different runway to go in the PRIMARY runway slot in the LAND SITE UPDATE items on BFS OVERRIDE governs the selection of TACAN stations.

3011/051
BFS OVERRIDE
5 003/01:20:00
BFS 000/00:10:00

IMU 1 2 3
DES 1 2 3

VENT DOOR CNTRL
OPEN 4
CLOSE 5

LAND SITE 6 PRI 19 EDW22
UPDATE 7 SEC 20 EDW17
8 ALT 21 NOR17

ET SEP
AUTO 9
SEP 10

ET LMS DR
CLOSE 11

ABORT MODE
AOA 12
ATO 13
ABORT 14

MAX THROT 24

FCS 15

Figure 5-5. BFS OVERRIDE Display - LAND SITE UPDATE

3041/050/
HORIZ SIT
5 003/01:30:00
BFS 000/00:15:00

ALTM
9 29.92

RWY CTR
EDW22 3*
EDW17 4
NOR17 5

TAEN TGT
GEN L DVHD 6
NSI L
NEP 7
AIM NOM 8

LOAD 16

NAV RESID	HAT	AUTH	HP	HP	HP	HP	HP	
TAC A2	2.2	0.1	19	20	21	157.1	156.8	157.0
RNG	1.0	0.2				201.3	202.0	201.8
DRAG H			22	23	24			
AOA 10-300		0.3	25	26	27			
AOA TO GPC			28	29	30			

Figure 5-6. BFS HORIZ SIT Display - Runway Designation

5.3 LANDING SITE UPDATE EXAMPLE

In OPS 2, the UNIV PTG display initially shows the I-loaded nominal EOM minitable.

L D G	S I T	U P D A T E
25	PRI 19	EDW22
26	SEC 20	EDW17
27	ALT 21	NOR17

If a decision were made to do a contingency landing at Kadena Air Base, the following CRT entry might be made.

ITEM (25) + 7 EXEC

The runway identifier for KAD05 is 7. The entry above loads KAD05 as the primary runway. It also loads the set of TACAN's listed below KAD05 in column 4 of figure 5-4. This set includes TACAN's for Kadena and Hawaii and all are loaded in the minitable. There is no MLS data for KAD05 and so no MLS data is transferred.

The runway identifier for KAD23 is 8 and the entry below loads it as the secondary runway.

ITEM (26) + 8 EXEC

There are only two maxitable runways in the Kadena area, so there is no point in updating the alternate runway.

The UNIV PTG display would now show:

L D G	S I T	U P D A T E
25	PRI 7	KAD05
26	SEC 8	KAD23
27	ALT 21	NOR17

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After proceeding to OPS 3, the HORIZ SIT display would show:

RWY
KAD05 3*
KAD23 4
NOR17 5

Since the update was done in OPS 2 (and can only be done in OPS 2 in the PASS), the BFS will not have the same runways in its minitable. To update the BFS landing site, the BFS is moded to OPS 301 and the BFS OVERRIDE display is called.

The display initially will show the nominal EOM table:

LAND SITE	6 PRI	19	EDW22
UPDATE	7 SEC	20	EDW17
	8 ALT	21	NOR17

The crew then would do an ITEM (6) + 7 EXEC to load KAD05 as the primary runway. This loads the TACAN listed in the CONT 3 minitable (figure 5-4). The runway identifier for KAD23 is 8 and the entry below loads it as the secondary runway:

ITEM (7) + 8 EXEC

The OVERRIDE display would now show:

LAND SITE	6 PRI	7	KAD05
UPDATE	7 SEC	8	KAD23
	8 ALT	21	NOR17

SECTION 6

BFS NAVIGATION DELTAS

The following is a summary of the differences in BFS navigation from PASS navigation:

1. Single state nav is used throughout mission
2. PASS to BFS state vector transfer capability
 - Pre-engage, MCC typically uplinks state vector update to PASS then has crew perform a PASS/BFS SV XFER instead of directly uplinking to BFS.
3. BFS entry nav management
 - ADTA-H and TACAN kept in INHIBIT to avoid possible state vector degradation due to sensor errors. PASS to BFS state vector transfer will be done as required to keep BFS state vector within tolerance
 - ADTA TO G&C placed in AUTO to be prepared for potential engage
 - If ADS unavailable, NAVDAD only (no default air data)
 - No MLS
4. Landing site update capability available in OPS 3 on BFS OVERRIDE Display
 - Same minitables as PASS (no MLS data)
 - BFS "listens" to changes made to PRI, SEC, ALT RNWY selection on PASS HSD
5. No orbit or rendezvous navigation.

SECTION 7

NAVIGATION CRT DISPLAY DESCRIPTIONS

In the following subsections, the primary CRT displays used with the navigation system will be described. Only those items or parameters related to nav will be included. The CRT displays to be covered include:

- HORIZONTAL SITUATION (PASS)
- HORIZONTAL SITUATION (BFS)
- OVERRIDE (PASS)
- BFS OVERRIDE
- RELATIVE NAVIGATION (PASS)
- S TRK/COAS CNTL (PASS)

7.1 HORIZONTAL SITUATION (PASS) SPEC 50

This CRT display provides Orbiter position and heading information with respect to the ground plane. It is also used to select primary, secondary or alternate runways and to manually load delta state vector updates. Also, it is used to monitor TACAN performance. In addition, the crew uses this display to monitor and control the Kalman filter with respect to drag altitude, ADTA, and TACAN data (see figure 7-1).

7.1.1 Runway Designation. The display has a runway designation data field that shows the designated landing site (RWY). Crew controls are also provided to allow the crew to redesignate the intended landing runway. The primary runway (Item 3), the secondary runway (Item 4), and the alternate runway (Item 5) are indicated by displaying the appropriate mnemonic. If the display is called up in MM 301-303, an "*" indicator will be displayed initially by the primary runway (Item 3) and thereafter shall reflect crew inputs.

7.1.2 Delta State Vector Update. Items 10 through 15 provide the capability to enter delta position and velocity components in runway coordinates. Only components requiring update need be entered, the remaining components being zeroed.

Item 16 (LOAD) provides the capability to execute a delta update to the navigated state of the Orbiter using the data entered in Items 10 through 15. Upon completion of the delta update by NAV, these items and their associated buffer shall be zeroed.

Item 18 (ΔT) provides the capability to update state vector downtrack errors by means of adding or subtracting a delta time in seconds. The update is performed after a time value is entered via Item 18 (ΔT) and verified, followed by the execution of control Item 16 (LOAD). The delta time display field is

zeroed when the display is first called and will be rezeroed upon completion of a delta time update by Entry Navigation. Item 18 is legal in OPS 3 only. Executing this item in any other OPS will cause an ILLEGAL ENTRY message to be generated.

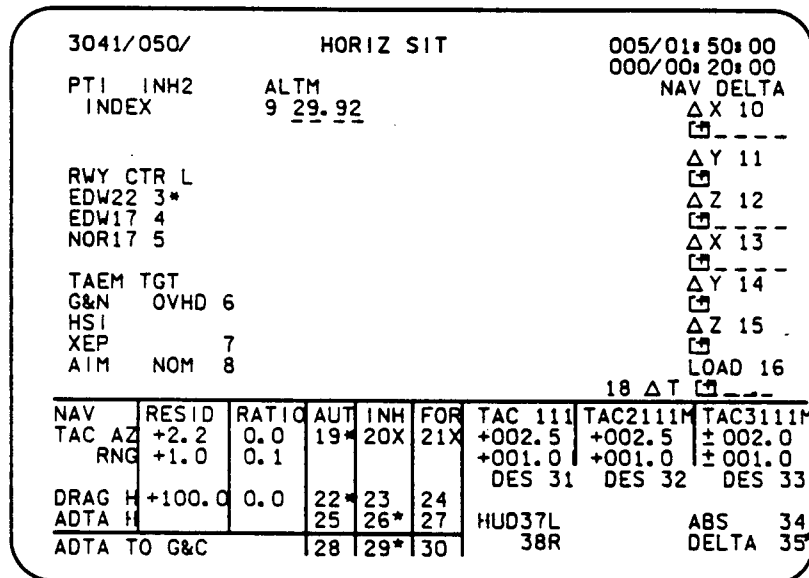
Item 17 (PASS/BFS SV XFER) does not appear on the PASS display and is illegal in the primary system. Any attempt to execute this item in the PASS will result in an "ILLEGAL ENTRY" message.

7.1.3 Nav Filter Controls. The RESID column contains the residual data value for each component of each data type that is being processed by the Nav filter. The residual is formed in navigation by subtracting the Nav estimate of the data from the selection filter output of the data. (It should be noted here that navigation uses the composite data output from the selection filter as inputs to the navigation filter so that no distinctions are made as to the LRU source of the data to the nav filter. In the two-LRU cases, the LRU data is averaged so that the data cannot be distinguished as to LRU.) The residual value gives the crew an indication as to how well the data and the nav estimate of the data agree. However, this data alone cannot identify whether the data or the nav estimate of the data is in error.

The RATIO column contains the edit ratio computed in navigation as the ratio of the data residual to the maximum allowable residual. If this ratio is less than one, the residual edit test performed by navigation on the data is passed, and the data is subsequently used to update the state vector. If the data fails the residual edit test, the ratio will be displayed as a number equal to or larger than one and will not be used to update the state vector. Thus, the edit ratio and the ratio parameter status indicators give the crew an indication of whether a particular data type is being incorporated into the state vector. The residuals and edit ratios are computed by navigation for each nav cycle and are available for display. When data is not being processed by the nav filter, the residual and ratio data fields for that parameter shall be blanked. A parameter status indicator column to the right of the RATIO will contain a down arrow and will disappear when the edit test is passed by a predefined percentage of "Good" data. The parameters defining percentage of "Good" data are I-loaded.

There are three filter control options: Auto (AUT); Inhibit (INH); and Force (FOR), which the crew can exercise on three data types: TACAN (TAC AZ and RNG), drag altitude (DRAG H), and baro altitude (ADTA H) to update navigation. Items 19, 22, and 25 (AUT) allow navigation to automatically select data to be used if it passes the edit test. Items 20, 23 and 26 (INH) preclude updating the state vector with the RM-selected data, but this data is used to generate the displayed residual and ratio values. Items 21, 24, and 27 (FOR) override the edit and force the data to be used to update the state vector if the data is being processed by the nav filter. Items 19-21, 22-24, and 25-27 are mutually exclusive. An asterisk(*) appears next to any Item (19-27) that has been selected. The display will be initialized with Items 20 (INH), 22 (AUT) and 26 (INH) selected.

Items 28-30 provide control over the source of air data parameters to Guidance and Flight Control. Item 28 (AUT) provides auto transition from Nav-derived air data to ADTA. Item 29 (INH) inhibits the ADTA data. Item 30 (FOR) forces the



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Figure 7-1. PASS HORIZ SIT Display

For each of the four ADTA LRU's, data is cyclically displayed to the crew to allow them to determine whether an LRU failed by RM is in agreement with the other LRU's and should be reselected and to aid in solving RM dilemmas. This data includes altitude in feet, angle of attack in degrees, and Mach number. A parameter status column after the LRU ID number shall be blank for normal operation, display a down arrow for an RM declared failure or crew deselection, display a question mark for an RM dilemma, or an "M" for missing data. There are four item numbers which allow the crew to reselect an LRU for use by the ADTA selection filter. These items are legal in MM 304, 305, 602 and 603. Execution of these items in OPS 1, MM 301, 302, 303 or 601 will result in an ILLEGAL ENTRY message.

For each of the IMU LRU's the following data is displayed cyclically to the crew to aid in solving RM dilemmas. A parameter status column is provided after each LRU ID number that shall be blank for normal operation, display a down arrow for an RM declared failure or crew deselection, display a question mark for an RM dilemma, or an "M" for missing data. The STAT column displays the output of Built-in-Test Equipment (BITE) Status word (hardware and software). The STAT column will either be blank for normal operation or display "BITE" to indicate a problem detected in the LRU. The ATT column has two parameters displayed, including which IMU is selected for use and whether the IMU data is good or not. There are three item numbers which allow the crew to reselect an LRU that has been declared failed by RM or to deselect an LRU for use by the IMU selection filter.

When an ADTA or IMU has been declared failed by RM, a down arrow will be displayed in the status column and an asterisk will be driven after the deselect/select item number to indicate that the LRU is failed and deselected. If the deselect/select item number is then executed, the LRU will be reselected and the down arrow and asterisk removed and the fail bit in RM is reset such that this LRU is used by the selection filter until such time that RM declares it failed again. If an LRU is deselected that is in a normal state or in a dilemma a down arrow will be displayed in the status column and an asterisk driven after the deselect/select item number.

The display will be initialized each time it is called with the current state of the LRU's that are deselected or selected. If no previous failure had occurred prior to calling this display in OPS 1 or 6, the display would show all LRU's selected. If an LRU was deselected during OPS 2 or 8, this LRU would still be deselected when this display is called in OPS 3. During OPS 1, the ADTA data will be blanked.

7.4 BFS OVERRIDE/SPEC 51

The BFS OVERRIDE display (figure 7-4) provides the capability to control the selection or deselection of an IMU for use in the IMU RM. It is available in OPS 1, 3 and 6.

Items 1, 2, and 3 provide the crew with the capability to select or deselect an IMU LRU for use by IMU RM. Execution of any of these items will cause the associated IMU to be deselected. An asterisk(*) is displayed beside the item number indicating deselection. The capability exists to re-select an IMU for use in RM although reselection of an IMU will not upmode the BFS IMU selection logic to the 3-level, in which the mid value selection is done. Re-selection is accomplished by re-executing the associated DES item. This action will also cause the asterisk to be blanked. Items 1, 2, and 3 are active in OPS 1, 3, and 6. They are initialized blank and will thereafter reflect the current select/deselect state as modified by crew entry.

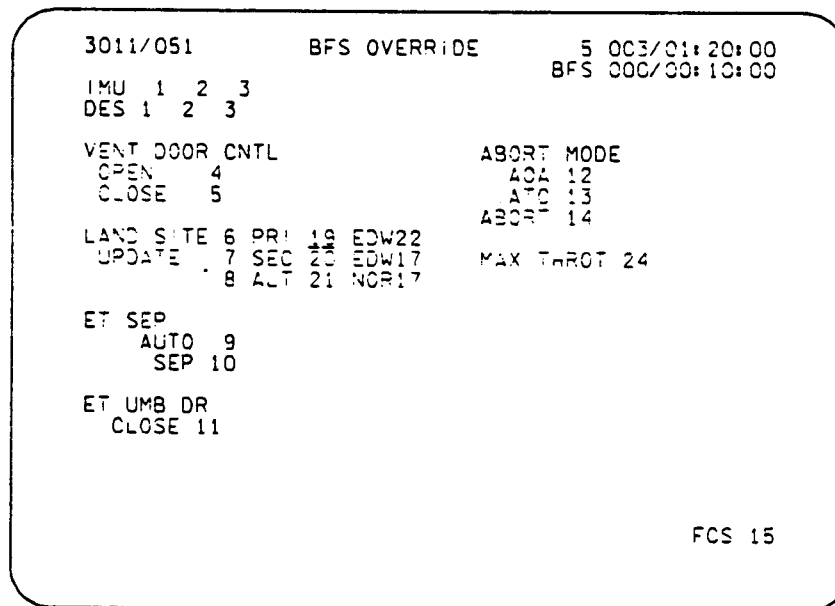


Figure 7-4. BFS OVERRIDE Display

7.5 RELATIVE NAVIGATION/SPEC 33

The REL NAV display provides data and controls for on-orbit/rendezvous navigation operations with the S TRK, RR, and COAS. On-orbit/rendezvous nav filter controls and state vector management controls are provided to allow manual control of navigation data from the S TRK, RR, or COAS depending on which instrument is being used. Thrust monitoring and the capability to enable the software to use the Ku-band for the rendezvous radar are also provided (figure 7-5).

- ① The relative motion information portion of this display is divided into two sections: current navigated relative state information, and relative motion parameters provided by the radar system. The following current navigated relative state information will be displayed if RNDZ NAV is enabled and updated every two seconds until the display is terminated via crew command. If RNDZ NAV is not enabled, these parameters will be blanked.

- Line-of-sight range (kft) between vehicles
- Range rate (fps) - the sign convention is negative for a closing rate and positive for an opening rate
- The angle between the projection of the Orbiter tracking body vector (selected on UNIV PTG) into the orbit plane and the local horizontal plane (0 to 360 degrees).
- Out-of-plane position - the current perpendicular distance between the Orbiter and the orbital plane of the target vehicle (kft); positive along the negative angular momentum vector of the target.
- Out-of-plane velocity - the current rate at which the Orbiter is moving relative to the target orbital plane (fps); positive along the negative angular momentum vector of the target.
- Time of the next Orbiter/target orbital nodal crossing (MET-hr:min:sec).

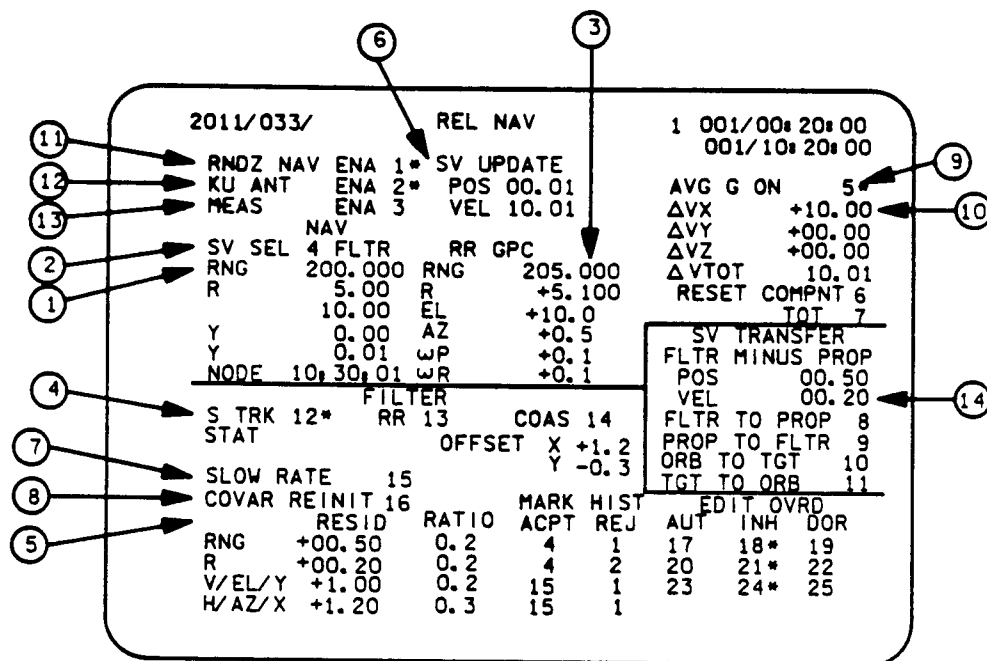


Figure 7-5. REL NAV Display

② Item 4 allows the crew to control the source of the navigated relative state data being displayed. The display is initialized with the data being derived from the "propagated" state vector, i.e., a navigated state vector that is not updated by the RNDZ NAV filter. This is indicated by the text PROP displayed next to item 4. Execution of item 4 changes the source of the navigated relative state data to the "filtered" state vector, i.e., a navigated state vector that incorporates RNDZ NAV filter data. This is indicated by the text FLTR displayed next to item 4. Item 4 acts as a flip-flop, alternately selecting the "propagated" and "filtered" state vectors as a data source. Item 4 controls the source of navigation data to the Universal Pointing specialist function and on-orbit guidance as well as the display.

③ The following current radar relative state information is initialized upon display callup and subsequently updated once per second until the display is terminated via crew command. A status symbol is provided to the right of each parameter as follows: a down arrow indicates loss of good data; "M" indicates that the radar system is in the COMM MODE or commfaulted; and a blank indicates that the data is good. The appropriate parameters are blanked if the radar system is not operative or if a specific parameter has a commfault associated with the data:

- a. Line-of-sight range (kft) between the vehicles
- b. Range rate (fps) - sign convention is the same as for the current navigated state above
- c. Pitch position (elevation) of the radar antenna gimbal relative to its null position (+90 deg); positive sense - antenna motion toward the +X Orbiter axis
- d. Roll position (azimuth) of the radar antenna gimbal relative to its null position (+180 deg); positive sense - antenna motion toward the -Y Orbiter axis
- e. Pitch inertial angle rate (+ mr/sec); positive sense - antenna motion toward the +X Orbiter axis (mr = milliradian)

The status of the radar system is displayed next to "RR." The status designation are discussed in detail in the KU RADAR 2102 lesson. In summary they will be one of the following:

- a. STST - Self test in progress. Any of the following status indicators will be overridden by self-test.
- b. COMM - Panel A7 Mode switch is in the COMM position indicating that the Ku-band antenna is being used for communications instead of as a rendezvous radar.
- c. GPC - The antenna steering switch is in the GPC position. Antenna pointing and search are under GPC control and the manual slew switches are inhibited.

d. GDSG - The antenna steering switch is in the GPC DESIG position. Antenna pointing and inertial stabilization are under GPC Control. The manual slew switches, programmed search function, and RF angle tracking are inhibited.

e. ATRK - The antenna steering switch is in the AUTO position. Antenna pointing is done via the manual slew switches, which are disabled when RF angle track is achieved.

f. MSLW - The antenna steering switch is in the MAN SLEW position. Antenna pointing is done via the manual slew switches. RF Angle track and inertial stabilization are inhibited.

④ This display contains data and controls required to monitor and select the sensors to be used for angular data by the rendezvous filter in state vector propagation (Items 12, 13, 14). The S TRK, RR, and COAS angle data are mutually exclusive; i.e., if the RR is selected, the appropriate item number will be tagged with an asterisk and the previously selected S TRK or COAS will be deselected and the appropriate asterisk blanked. Upon initial display call-up, the S TRK shall be selected. The appearance or removal of an asterisk will have a time delay depending on the RNDZ NAV processing rate.

This rendezvous angle sensor block contains other information used to monitor S TRK and COAS operation. The "status" remote text readout indicates the currently selected S TRK status (-Y or -Z S TRK previously selected to the Target Track Mode on the S TRK/COAS CNTL display) and will display the following: (blank), ST FAIL, ST PASS, NO TARGET, FALSE TRK, OUT FOV, HI RATE. A separate status display field provides a "BITE" indication on the selected S TRK. Also displayed are two offset angles that represent the displacement of the target being tracked by the -Z S TRK in the -Z COAS FOV. This offset data is driven only when the -Z Star Tracker has been selected for either the Star Track mode (Item 4) or the Target Track mode (Item 6) on the STRK/COAS control display. Otherwise, the display is blanked.

⑤ On-Orbit/RNDZ NAV filter data, status, and controls are also displayed. Since only a single instrument (RR, S TRK, or COAS) may be used at a time to supply angle data, the angle data being displayed is only for the instrument selected. RR range and range rate data are always available to nav as long as their respective "data good" indications are present. RR range and range rate data and S TRK, RR, or COAS angle data are used to update the state if the respective data pass a residual edit test in nav. Data from the RR and S TRK are automatically requested by nav for processing. COAS marks are executed manually by the crew centering the target in the COAS FOV and pressing the "ADI ATT REF" pushbutton. When the COAS is selected for input to nav, the computation of a new ADI reference is inhibited.

The residuals formed in nav by subtracting the nav estimate of the measurement from the observed measurement are displayed for RR range and range rate and S TRK, RR, or COAS angle parameters for the instrument selected.

The ratio is computed by the on-orbit rendezvous navigation software and is displayed and used for editing bad data. The edit test for the processing of

measurement data is computed in one of two ways, depending upon the status of the force control on the REL NAV display. The nominal residual edit test is applied when the force control is "OFF". The edit test criterion is relaxed when the force control is "ON". Data passing the residual edit test is used to update the state vector and covariance matrix. If the data fails the residual edit test, the residual and ratio data will be displayed but the data will not be used in the update process. Residual and ratio data are blanked anytime RNDZ NAV is inhibited.

MARK HIST data are also displayed. This data reflects the number of NAV marks that have been accepted or rejected for a data type by the NAV filter.

A status indicator on the rejected data is driven as a down arrow when an "I-loaded" number of sequential marks are rejected and removed when the mark is forced and accepted or an "I-loaded" number of sequential acceptable marks occur. The ACPT/REJ counters are reset to zero when a target or orbiter state vector is changed by uplink or by the crew; a target-to-orbiter, Orbiter-to-target or PROP TO FLTR state vector transfer is performed; rendezvous navigation is enabled; a covariance matrix reinitialization is performed; or after a delta velocity burn. The ACPT/REJ counters for angle data are also reset to zero whenever the input data source is changed (e.g., COAS marks are selected in place of S TRK marks). The ACPT/REJ counters are blanked when RNDZ navigation is inhibited.

There are three crew controls each for range, range rate, and angle data which provide Auto (AUT), Inhibit (INH), and Force (FOR) capability. When a crew selection is made, an asterisk is driven after the selected item number. The appearance or removal of an asterisk will have a time delay depending on the NAV processing rate. The AUT, INH, and "FOR" functions are mutually exclusive for any one parameter set (i.e., V/EL/Y, H/AZ/X, RNG, R DOT); consequently, an asterisk may never be tagged to more than one of these three items simultaneously. When the display is initially called, the "INH" item numbers will be automatically selected. The "INH" function causes data to be presented to the filter for processing in order to generate residual and ratio data for display, but it will not be used to update the state vector nor will the reject counter be incremented. The "AUT" function allows for automatic processing of data in the nav filter. The "FOR" function will relax the edit test criterion based upon the value of the residual ratio from the last data point. Data will be processed if the current residual passes the new edit test criteria. The "FOR" function, when executed, stays in effect only for the next data point. Then control reverts to the previously executed function (either "AUT" or "INH"). The asterisk will be driven in the "FOR" column for only one nav processing cycle.

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- ⑥ Two parameters, SV UPDATE POS and VEL, display the magnitude of the change to the filtered data vector position (POS) and Velocity (VEL) made by the Rendezvous Nav filter in the last computation cycle.
 - ⑦ Also included on the display is a single item control (Item 15) that allows the crew to switch the rate at which rendezvous navigation processes marks. Execution of this item causes the other rate to be used (i.e., a flip-flop). An asterisk is displayed next to item 15 when navigation is processing marks

at the slower rate. The appearance or removal of the asterisk will have a time delay depending on the processing rate. If rendezvous navigation is not enabled, execution of this item will be illegal. This item is being made nonfunctional as it has been determined that it is not necessary.

- ⑧ Item 16 (COVAR REINIT) provides the control for reinitialization of the covariance matrix. An asterisk(*) will be driven next to this item number while the covariance matrix is being reinitialized. The appearance or removal of this asterisk will have a time delay depending on the nav processing rate. The asterisk(*) will be displayed for one nav cycle. This capability is required in addition to the reinitialization which occurs whenever rendezvous navigations is enabled. If rendezvous navigation is not enabled, execution of this item will be illegal.
- ⑨ Item 5 provides the capability to initiate and terminate powered-flight navigation (AVG G) for thrust monitoring in MM 201. This item control is legal only in MM 201. An asterisk will be driven after the item number when powered flight navigation is enabled. The display will be initialized with powered flight navigation ON each time MM 201 is entered. In Major Mode 202, powered-flight navigation will be enabled and an asterisk will be displayed after Item 5 whenever the display is called. The appearance or removal of the asterisk will have a time delay depending on nav processing rate.
- ⑩ A translation thrust monitor capability is also provided. Four digital counters (registers) are used to accumulate total velocity gained and the velocities gained along the respective X, Y, and Z body component axis. The component registers increment and decrement according to the sense of the velocity change. The total velocity register accumulates all body axis velocity changes and only increments, regardless of the sense of the velocity change; i.e., $\Delta VTOT = |\Delta Vx| + |\Delta Vy| + |\Delta Vz|$. In addition, VTOT counts up at a rate of 1 fps/min continuously and thus is next to useless. Two item number controls are provided; one which simultaneously resets the component registers to zero and one which only resets the total velocity register to zero. These four registers are zeroed upon initial display callup. Subsequent display callups will reflect the current values of delta velocity.
- ⑪ Item 1 provides the control for enabling and disabling all the principal functions required to support rendezvous navigation. When rendezvous navigation is enabled, an asterisk will be driven next to the item number. When the item number is re-executed, the asterisk will be removed, rendezvous navigation support software will be disabled, and orbit navigation will be enabled. When the display is first called, rendezvous navigation will be disabled. The appearance or removal of this asterisk will have a time delay depending on the nav processing rate.
- ⑫ Item 2 provides the control to enable or inhibit GNC angle pointing data from being transferred between the GNC and the SM GPC's. This is accomplished using the Intercomputer Communication (ICC) data buses. When the display is first called, the GNC angle pointing data transfer will be inhibited. An asterisk shall be displayed after the item number whenever GNC angle pointing data transfer is enabled.

⑬ Item 3 provides the control to enable/inhibit navigation from incorporating measurements while in Major Mode 202. Upon return to Major Mode 201, this item is set to inhibit. If the measurement enable item is executed in Major Mode 201, an operator error shall be generated. When the display is first called, this item will be initialized inhibited. An asterisk will be driven next to this item number whenever navigation measurement incorporation is enabled in MM 202. The appearance or removal of this asterisk will have a time delay depending on the nav processing rate. If rendezvous navigation is not enabled in MM 202, execution of this item will be illegal.

⑭ Four item controls are provided for the transfer of state vectors. Item 8 transfers and overwrites the filtered state vector into the propagated state vector slots, and, Item 9 transfers and overwrites the propagated state vector into the filtered state vector slots. The filtered state vector is a state vector that incorporates RNDZ NAV filter data derived from Rendezvous Radar, Star Tracker or COAS measurements. The propagated state vector is a separate state vector which is not updated by RNDZ NAV filter inputs. The filtered and propagated state vectors will be either the Orbiter or target state vector depending on the value of a mission-dependent I-Load. Typically, the Orbit state vector will be filtered.

Item 10 transfers and overwrites the Orbiter state vector into the target state vector slots and Item 11 transfers and overwrites the target state vector into the Orbiter state vector slots. For these two transfers, only the filtered state vector will be involved. Whenever any of the four transfer items is 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 being 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 rendezvous navigation is enabled. Two parameters, FLTR MINUS PROP POS and VEL, indicate the difference between the propagated and filtered state vectors. Once the nav filter has converged, these parameters can be used to determine when to update the propagated state with the filtered state.

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7.6 STAR TRACKER/COAS CONTROL/SPEC 22

The purpose of this display is to monitor and control the Star Tracker operation and moding. The display also provides data and controls necessary to perform COAS sightings and calibration. It is available in the PASS in OPS 2 and 3 (figure 7-6).

The upper left-hand portion of the display contains the controls necessary to mode the Star Trackers into the various submodes. Items 1 and 2 allow selection of the self-test (SELF-TEST) mode for the -Y and -Z star trackers, respectively. An asterisk(*) will be displayed after each item number to indicate that the self-test mode is active for that tracker. The self-test mode will remain active until completed and will be restarted each time Item 1 or 2 is executed if self-test is complete. The results of self-test will be shown elsewhere on the display.

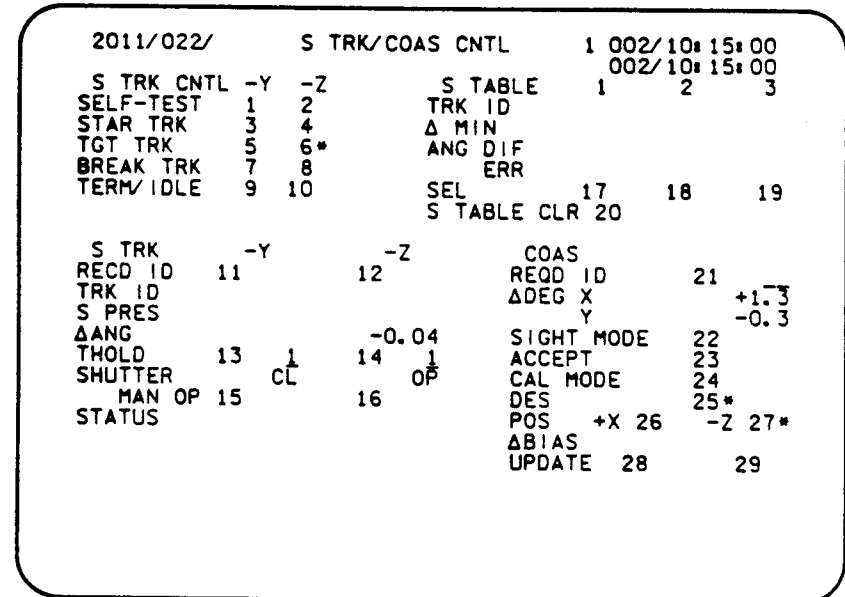


Figure 7-6. S TRK/COAS CNTL Display

Items 3 and 4 provide the crew with the means to select the ST mode of operation. This mode is selected to accomplish star tracking whenever the vehicle's attitude is known within 0.5 degree. Stars in both the -Y and -Z trackers may be tracked simultaneously. Items 5 and 6 are used to select the Target Track (TGT TRK) submode. This mode is used to perform target tracking with the Star Tracker for rendezvous. The program will allow a star to be tracked by one star tracker and the target by the other. An asterisk is displayed after each of these item numbers to indicate the current active mode. The asterisks will remain until the appropriate submode is terminated by the selection of another submode.

Items 7 and 8 are crew controls used to force the Star Tracker to break track (BREAK TRK). When this command is executed, the appropriate Star Tracker will break lock with the star currently being tracked and will resume tracking the next star encountered in the search pattern. Execution of a break track command will not change the selected submode.

Items 9 and 10 are the controls used to select the terminate/idle (TERM/IDLE) submode. Selection of this mode will cause all Star Tracker processing to be terminated except that required for Built-In Test Equipment (BITE) processing and will terminate any other submode in progress. An asterisk(*) will be displayed after each item number to indicate when the TERM/IDLE mode is selected.

Below the submode controls, in the lower left-hand portion of the display, are data and controls to monitor and control the ST functions. Identical data and controls are provided for each ST independently. Items 11 and 12 are the inputs used to enter the ID (REQD ID) of a desired star to be tracked. This input may be used in conjunction with the Star Track or target track modes to select the desired source. Entering zero into the ID location causes the software to compute its own stars based on availability.

The Required ID data field shall be zeroed upon completion of the Star Tracker manual mode processing. The star ID (TRK ID) outputs a code indicating which star or target is currently being tracked. The output code corresponds to any of the 50 catalog stars as well as to a rendezvous target. In the absence of a valid star or target ID, the ID field shall be zeroed. The TRK ID data field shall be zeroed upon completion of the Star Tracker manual mode processing. The star present (S PRES) location outputs an asterisk(*) whenever a star is being tracked by the Star Tracker.

Below the star ID and star present parameters are displays of the star position in the Star Tracker field of view. The delta angle (Δ ANG) output displays the angle between the expected star line-of-sight and the actual measured line-of-sight. For stars, expected line-of-sight is based on vehicle attitude and Star Tracker SOP-computed line-of-sight. For targets, expected line-of-sight is based on vehicle attitude and nav estimates for the rendezvous target. This parameter, (Δ ANG), is a measure of how well the vehicle's attitude is known and may be used to indicate if an alignment is required when a star is being tracked.

Items 13 and 14 are the control inputs used to enter a magnitude threshold for star or target tracking. Valid inputs are 0, 1, 2, or 3.

Below the threshold inputs are locations indicating the (SHUTTER) position for each Star Tracker. The display will show either "OP" (for open) or "CL" (for closed) to represent the current shutter position. Items 15 and 16 are controls that allow the crew to select the manual operating mode (MAN OP) of the shutter. Nominally, the shutter will operate in the automatic mode. Entry of either Items 15 or 16 will inhibit the automatic shutter mode for the appropriate star tracker and cause the shutter to be commanded and held in the open position. An asterisk(*) will be displayed next to the appropriate item number to indicate that the shutter is being forced open. The automatic mode may be reselected by re-executing the appropriate item number. This action will return control of the shutter to the hardware/software system, and simultaneously cause the associated asterisk(*) to be blanked.

Below the shutter controls, the display contains (STATUS) information from both Star Trackers. The location displays any of the following as appropriate: "ST FAIL" to indicate that a Star Tracker has failed self-test; "ST PASS" if self-test is passed; "FALSE TRK" if a star or target fails to pass position or rate reasonableness tests; "OUT FOV" if the input star or target is determined to be outside the Star Tracker FOV; "HI RATE" if the IMU-derived body rate exceeds 0.2 deg/sec (which results in degraded Star Tracker operations); "NO TARGET" if a target or a star is in the field-of-view but has not been acquired; and blank, which is the normal status state.

Directly below the status display is the BITE output location. This location displays "BITE" when any of the Built-In Test Equipment discretes indicates that a failure has been detected. The output indication will be driven double over-bright. If no BITE discrete indicates a failure, the display locations will be blanked.

The outputs and item entries to monitor and control the Star Table (S TABLE) are shown on the upper right-hand portion of the display. This data is presented in three columns where the left-most column (1) represents the current or most recent data. Columns 2 and 3 represent progressively older data. The track ID (TRK ID) shows the star ID code associated with each star in the table. Below the star ID is an output (Δ MIN) showing how old each input is in minutes. The clock starts incrementing from the time tag associated with the saved data.

The angular difference (ANG DIF) output displays the measured separation angle between the two stars. For example, the ANG DIF output in Column 1 shows the angular difference between the line-of-sight vectors of the stars in Columns 1 and 2. The same relationship applies to the angle difference of Columns 2 and 3. Column 3 "wraps around" to show the difference between Table Locations 3 and 1. Angle error (ANG ERR) is defined as the difference between the ANG DIF computed from the star catalog and the ANG DIF computed from the Star Tracker measurements.

Items 17, 18 and 19 are controls used to select which star pair is to be used by the software to compute the alignment data. Nominally, the alignment software picks the best star pair based on predefined criteria. The two automatically selected stars will be indicated by asterisk's alongside the item numbers in the associated star table column. The crew has the capability to modify the automatic pair selection by executing the appropriate item entries. The item

numbers will act as flip-flops; i.e., each subsequent item entry will cause the selection logic to change states. For example, if the software logic had selected star table entries 1 and 3 and the crew wanted to force Entries 2 and 3, the initial display would show asterisks alongside Items 17 and 19. The crew would first execute Item 17, which would deselect Entry 2 and blank the displayed asterisk. The next step would be to execute Item 18 which, since the column was previously deselected, would cause the table entry 2 data to be selected and would cause an asterisk to appear next to Item 18. Therefore, Column 1 has been deselected and Columns 2 and 3 (which were previously selected) are used to compute the alignment. The selection will remain in force until a new star is tracked and input to the table, at which time the system reverts to automatic selection. Item 20 clears all data from the star table for both star tracker and COAS sightings.

The lower right-hand portion of the display contains the controls and data necessary to accomplish COAS sightings and calibration. Item 21 (REQD ID) allows the crew the means to input the star or target on which COAS marks are to be made. The star/target codes used are identical to those used in Items 11 and 12.

The Δ DEG X and Y output parameters display the equivalent -Z COAS offsets of a star or target being tracked by the -Z star tracker. These parameters allow the crew to visually locate in the -Z COAS the same object currently being tracked by the star tracker.

Item 22 is the input used to select the COAS (SIGHT MODE). In this mode, the ADI ATT REF button performs the COAS mark function. Star data obtained via COAS sightings and marks go directly into the star table. An asterisk is displayed alongside the item number to indicate that the sight mode is active. When the ADI ATT REF pushbutton is used to take COAS marks, the computation of new ADI reference is inhibited. Item 6 for the target track submode and Item 22 for the COAS SIGHT mode (with the -Z POS selected) are mutually exclusive; i.e., the selection of any single optical instrument (ST or COAS) deselects the other optical instrument and changes the asterisk configuration accordingly. Item 23 (ACCEPT) accepts the last COAS mark and allows processing of the "mark" data. As long as the ACCEPT command has not been executed, subsequent marks will override the previous marks. The ACCEPT command applies to the COAS star sight mode only and not when the COAS is being used for marking on a rendezvous target. This display is driven from the STAR TRACKER or COAS submodes.

Item 24 is used to select the COAS calibration mode (CAL MODE). Selection of this mode also reassigns the function of the ATT REF button as a COAS mark. Marks taken in this mode are used to update the COAS line-of-sight in nav-base coordinates. An asterisk is output alongside the item number to indicate that the calibration mode has been selected. When the ADI ATT REF pushbutton is used to take COAS marks, the computation of a new ADI reference is inhibited. Items 22, 24, and 25 are mutually exclusive.

Item 25 (DES) is used to deselect the COAS. When the COAS is deselected, an asterisk appears beside Item 25. Either Item 22 or 24 removes the COAS from the deselect state and blanks the deselect asterisk. Items 26 and 27 are controls used by the crew to specify the mounting position (POS) of the COAS,

either +X or -Z, respectively. An asterisk(*) is displayed alongside the appropriate item number to indicate which location has been selected.

The calibration (Δ BIAS) output displays the angular difference between the pre-flight calibrated COAS line-of-sight and the in-flight measured calibrated COAS line-of-sight in nav-base coordinates. The crew uses this information to determine any change in the COAS mount due to launch loads (vehicle bending, warp). Items 28 and 29 (UPDATE) are used to incorporate the new COAS Δ BIAS for the associated mounting position (POS +X or -Z). Incorporation of the data may be verified by noting that the Δ BIAS output is zeroed.

ACRONYMS

A/I/F Auto/Inhibit/Force
 ADI Attitude Director Indicator
 ADTA Air Data Transducer Assembly
 ALT Alternate
 AMI Alpha/Mach Indicator
 AOA Abort Once Around
 AOS Acquisition of Signal
 APU Auxiliary Power Unit
 AVVI Altimeter Vertical Velocity Indicator

BFS Backup Flight System
 BITE Built In Test Equipment

c.g. Center of Gravity
 COAS Crew Optical Alignment Sight
 CSS Control Stick Steering

DK Display Keyboard

EAS Equivalent Air Speed
 EOM Equation of Motion
 ET External tank
 ET SEP External Tank Separation

FCS Flight Control System
 FLTR Filter
 FOB Field of View
 FPS feet per second

G&C Guidance and Control
 GPC General Purpose Computer

h Altitude
 h Altitude rate
 HSD Horizontal Situation Display

I/O Input/Output
 IMU Inertial Measurement Unit

KFT thousand feet
 KSC Kennedy Spacecraft Center

LRU Line Replaceable Unit

M Mach
 MCC Mission Control Center
 MECO Main Engine Cutoff
 MET Mission Elapsed Time
 MLS Microwave Landing System

MM Major Mode
 MSL Mean Sea Level
 M50 Mean of 1950

nav Navigation
 n.mi. Nautical Mile

OFT Orbital Flight Test (OFT)
 OMS Orbital Maneuvering Subsystem
 OPS Operational Sequence

PASS Primary Avionics Software System
 PRI Primary
 PROP Propagated

\bar{q} dynamic pressure

RCS Reaction Control System
 RF Radio Frequency
 RM Redundancy Management
 RNG Range
 RR Rendezvous Radar
 RTLS Return to Launch Site

SEC Secondary
 ST Star Tracker
 STS Shuttle Transportation System

T/R Transmit/Receive
 TACAN Tactical Air Navigation
 TDRS Tracking & Data Relay Satellite

UPP User Parameter Processing
 α angle of attack