A REVIEW OF THE SPACE SHUTTLE ORBITAL FLIGHT CONTROL SYSTEM (FCS)

by

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Based on October 1983 Report CSDL-P-1786

Prepared for MIT A/C Systems Engineering Course 16.885J

November 3, 2005

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Presentation Applicability Note

The orbital FCS and associated avionics design as documented in this presentation are representative of the implementation at the beginning of the Space Shuttle flight program

- **Some notes have been included regarding specific upgrades later in the flight program**

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Topics of Discussion

- **Overview**
  - **Location or orbiter FCS-related systems**
  - **Orbital flight phases**
  - **Requirements for orbital FCS**
  - **FCS modes and submodes**
  - **FCS hardware and software interfaces**
- The FCS actuators and sensors
- Summary of the Digital Autopilot (DAP)
- Electronic stringing
- Cockpit views

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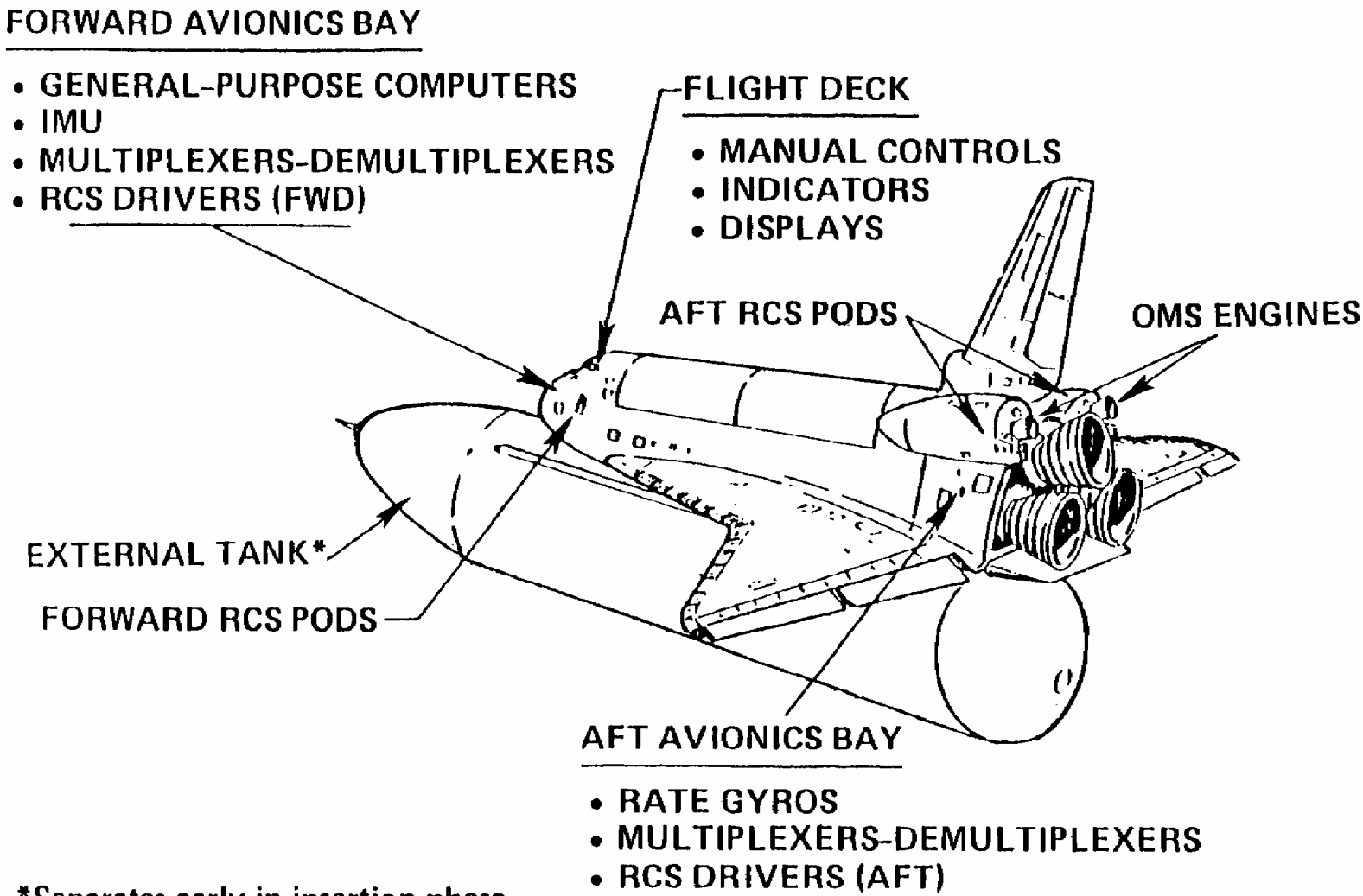
Location of Orbiter FCS-Related Systems



*Separates early in insertion phase

(Derived from SD72-SH-0105-1 Book 2-1B)

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Orbital Flight Phases: Insertion

- Begins at main engine cutoff (payload bay doors are closed)
- Includes:
  - Combined Orbiter/External Tank (ET) rotation control
  - Orbiter/ET separation
  - First and second Orbital Maneuvering System (OMS) burns (raising the orbit to the initial operational altitude)
- All sensors are available, including the Rate Gyro Assemblies (RGAs) which are required during ascent
- All General-Purpose Computers (GPCs) are active for maximum redundancy
- Vernier Reaction Control System (RCS) jets are not active
- Insertion ends after the second OMS burn, with a switch to the on-orbit mode

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Orbital Flight Phases: On-Orbit

- Payload bay doors are usually open
- Spans all payload operations
- Power consumption is minimized to conserve fuel cell reactants
  - RGAs are inactive
  - Two of the five GPCs are usually inactive
  - Two of the three Inertial Measurement Units (IMUs) are inactive except for mission-critical maneuvers
- Vernier RCS (VRCS) jets are available

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Orbital Flight Phases: Deorbit

- Payload bay doors are closed
- The deorbit burn is performed
- The forward Primary RCS (PRCS) may perform a propellant dump for vehicle center of gravity management
- All sensors are available including RGAs which are required during entry
- All GPCs are active for maximum redundancy
- VRCS jets are not active
- The Deorbit phase ends at entry interface (about 400,000 ft)

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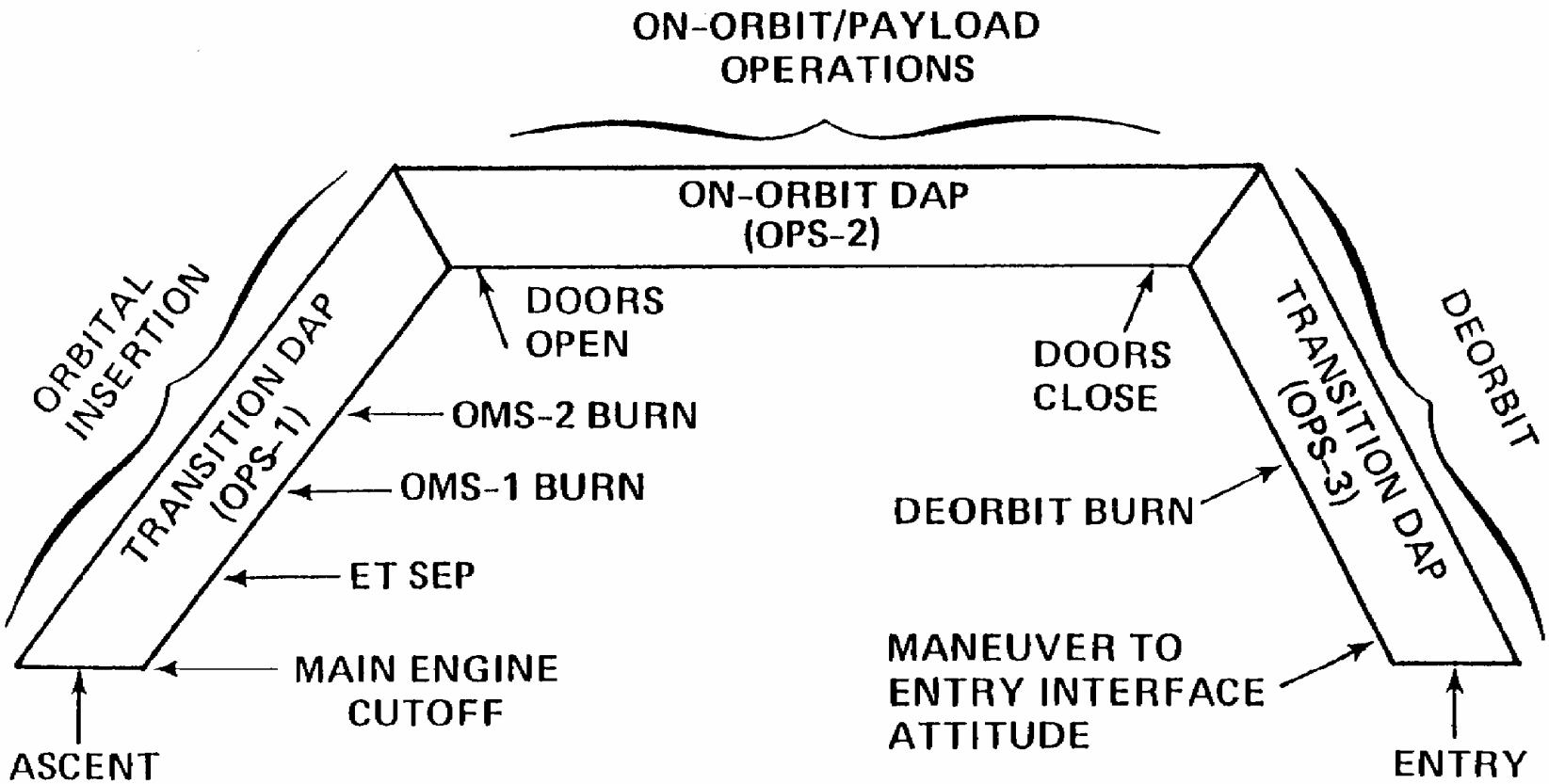
Transition and On-Orbit Digital Autopilot (DAP): Typical Flight Profile



Separation of DAP software by flight phase driven by 104K word memory limit of GPC memory on initial Shuttle orbital flights

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Major Requirements for Orbital FCS

- Two DAPs for three flight phases
  - Transition (for insertion and deorbit)
  - On-Orbit (for all payload operations)
- Failure tolerance
  - First failure: Remain operational
  - Second failure: Assure safe execution of all safety critical flight activities
- Control vehicle rigid body attitude and velocity changes to within specifications
- Operate at an 80 ms DAP cycle rate
- Adhere to hardware constraints
  - Limit the OMS actuator cycle rate to about 1 Hz
  - Limit the RCS activity to three simultaneous jet firings per pod

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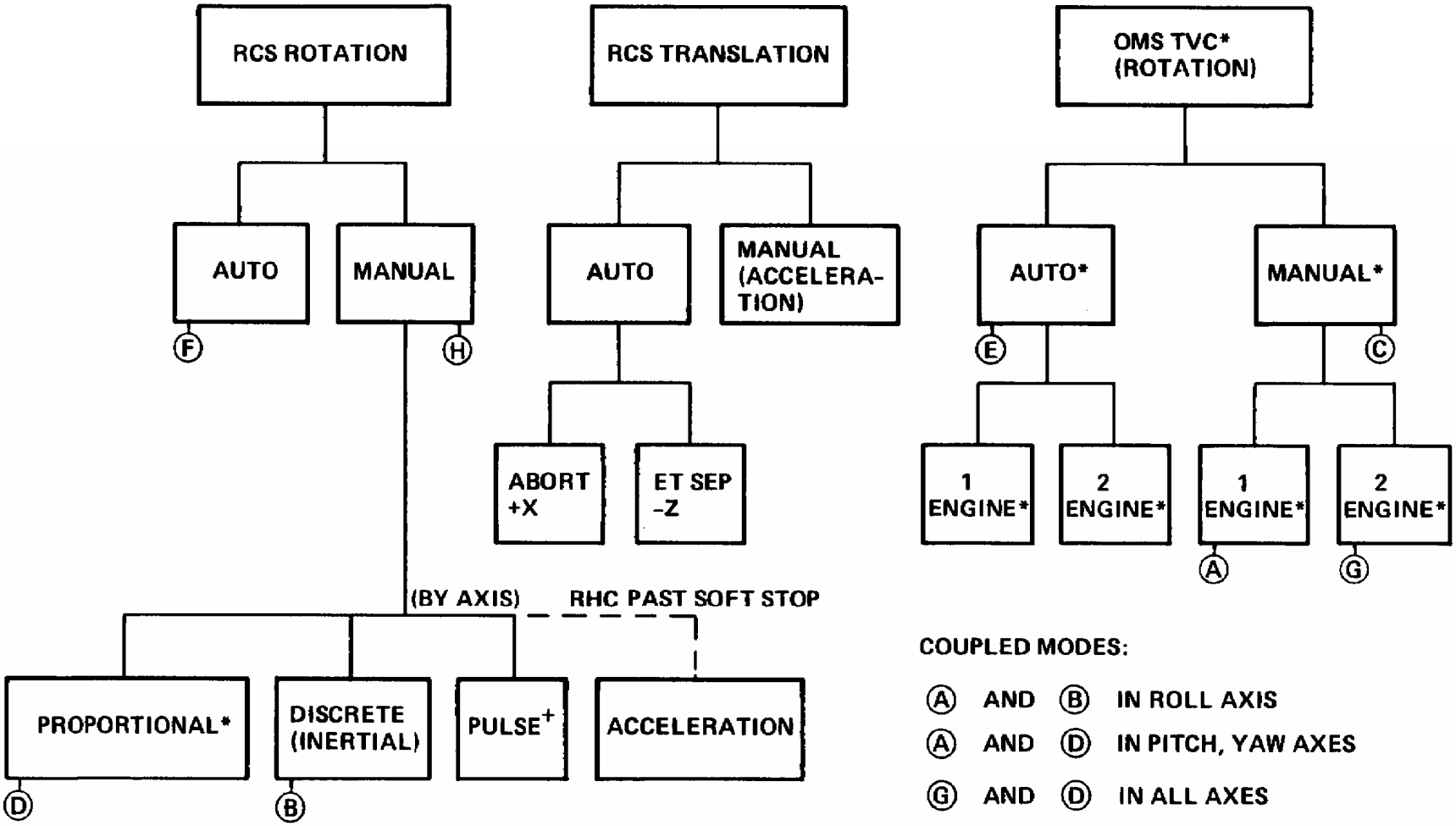
Transition FCS Modes



COUPLED MODES:

- Ⓐ AND Ⓑ IN ROLL AXIS
- Ⓐ AND Ⓓ IN PITCH, YAW AXES
- Ⓖ AND Ⓓ IN ALL AXES
- Ⓔ AND Ⓕ
- Ⓒ AND Ⓗ

* MODE AVAILABLE ONLY IF OMS THRUSTING

\+ MODE AVAILABLE ONLY IF OMS NOT THRUSTING

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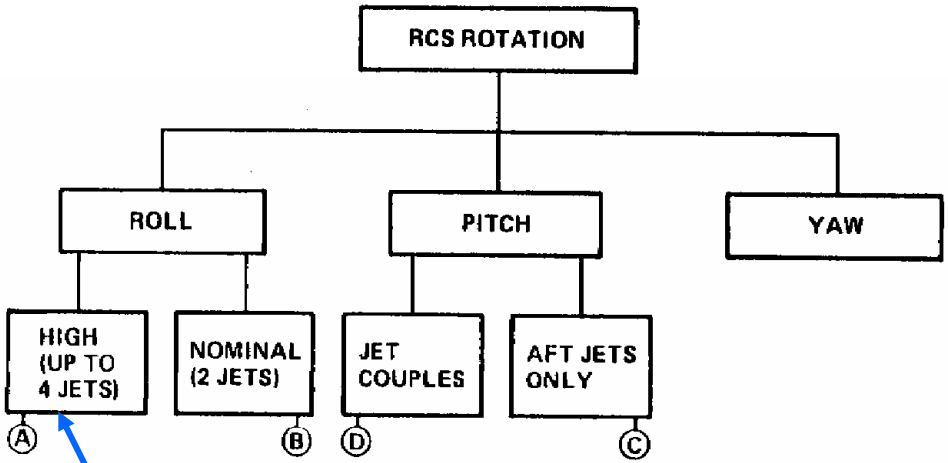
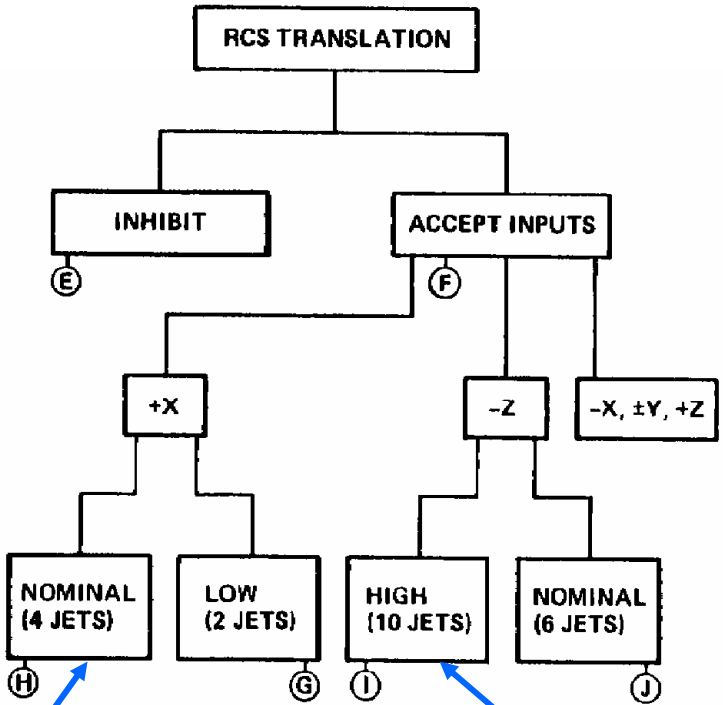
Transition FCS Submodes



Enables rate damping of Orbiter/ET stack after main engine cutoff

A – MATED COAST ONLY
B – NOT A
C – COMBINED WITH -X
D – NOT C



Provides deorbit backup if both OMS engines fail

Used for ET separation

E – DURING DEORBIT FORWARD RCS PROPELLANT DUMP
F – NOT E
G – DURING RCS/RCS PROPELLANT CROSSFEED
H – NOT G
I – THROUGH ET SEPARATION
J – NOT I

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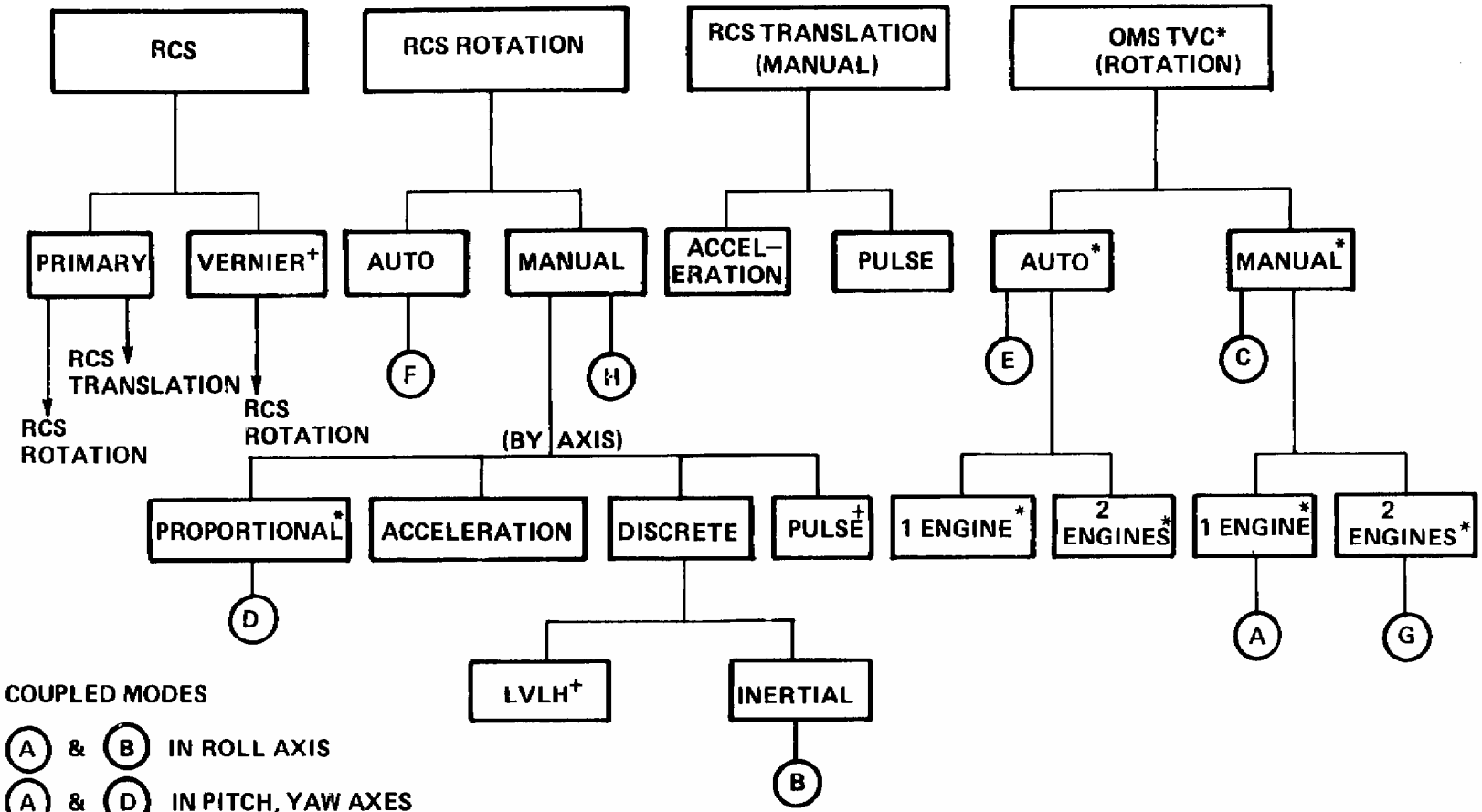
On-Orbit FCS Modes



COUPLED MODES

- (A) & (B) IN ROLL AXIS
- (A) & (D) IN PITCH, YAW AXES
- (G) & (D) IN ALL AXES
- (E) & (F)
- (C) & (H)

* MODE AVAILABLE ONLY IF OMS THRUSTING

\+ MODE AVAILABLE ONLY IF OMS NOT THRUSTING

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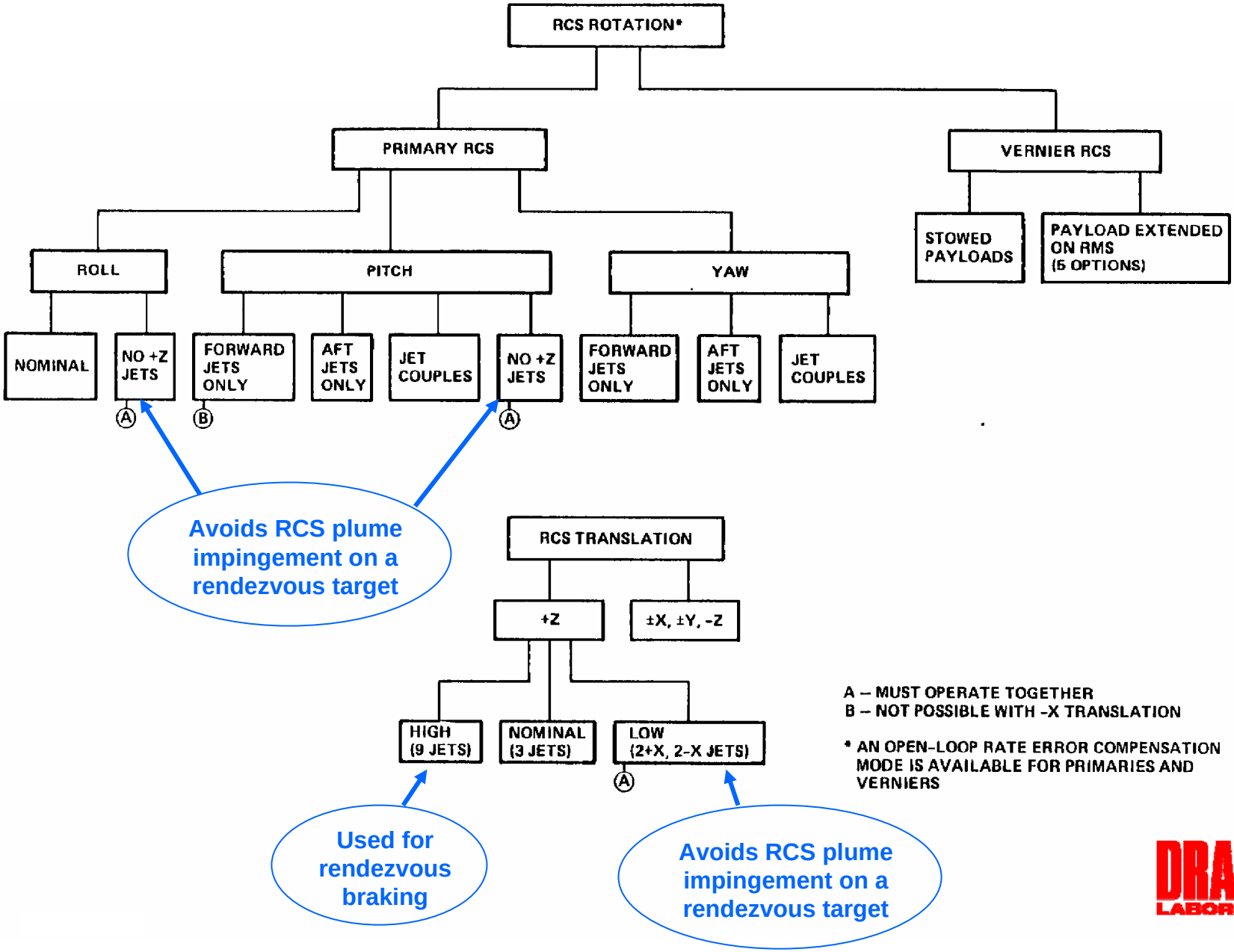
On-Orbit FCS Submodes



A – MUST OPERATE TOGETHER
B – NOT POSSIBLE WITH -X TRANSLATION

* AN OPEN-LOOP RATE ERROR COMPENSATION MODE IS AVAILABLE FOR PRIMARIES AND VERNIERS

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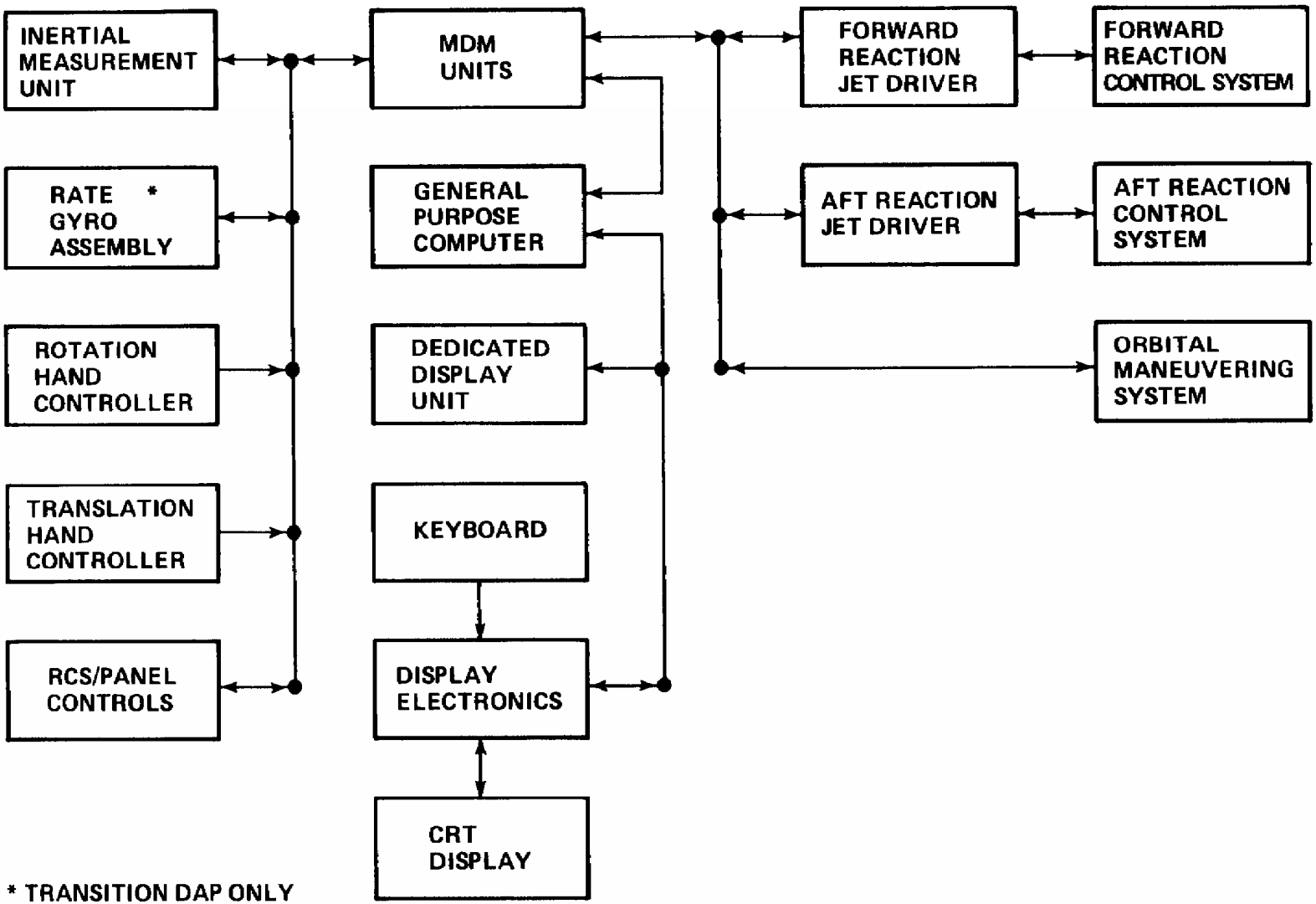
FCS Hardware Interface Diagram



* TRANSITION DAP ONLY

(DERIVED FROM SD72-SH-0105-1-BOOK 2-1B)

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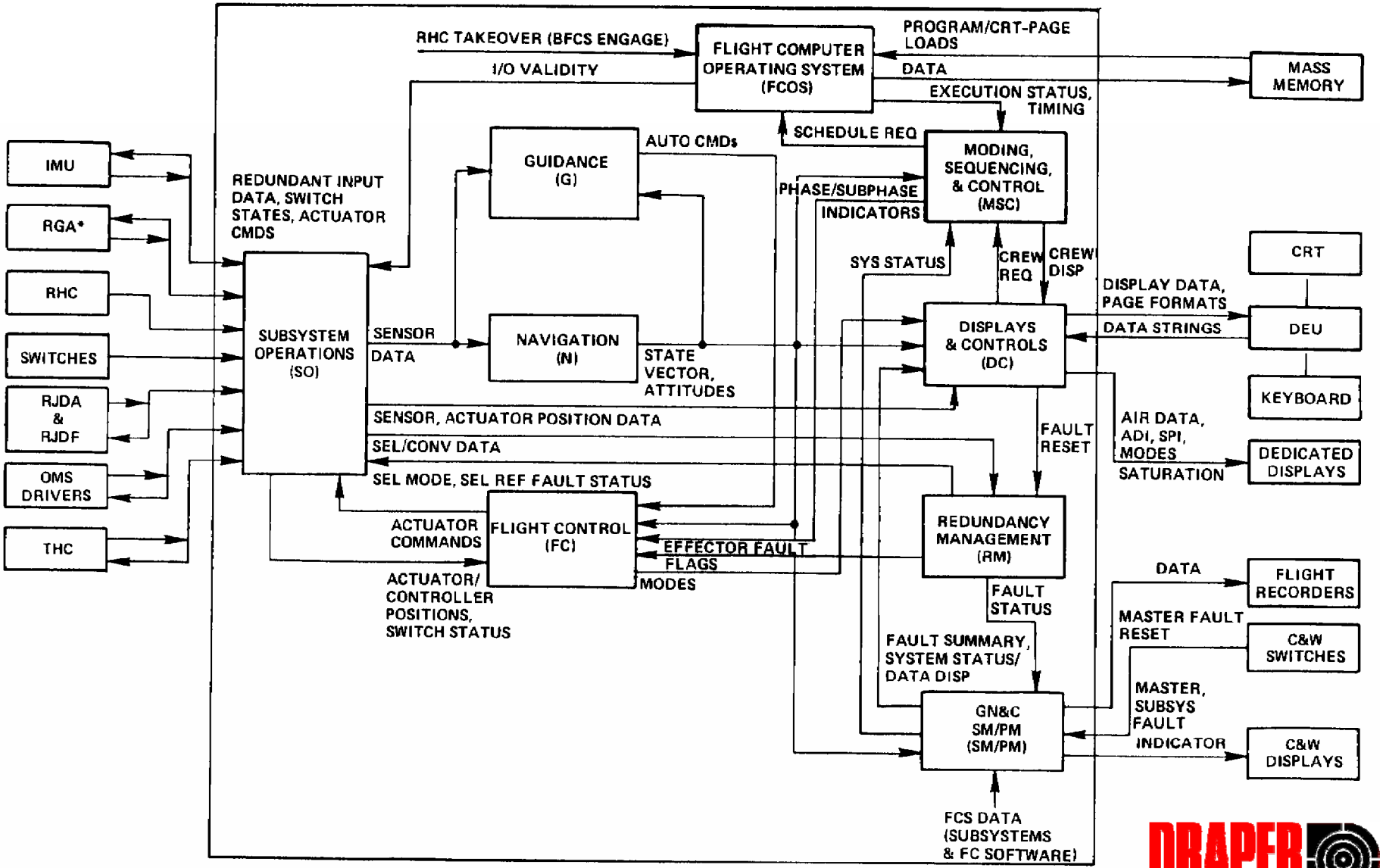
FCS Software Interface Diagram



* TRANSITION DAP ONLY

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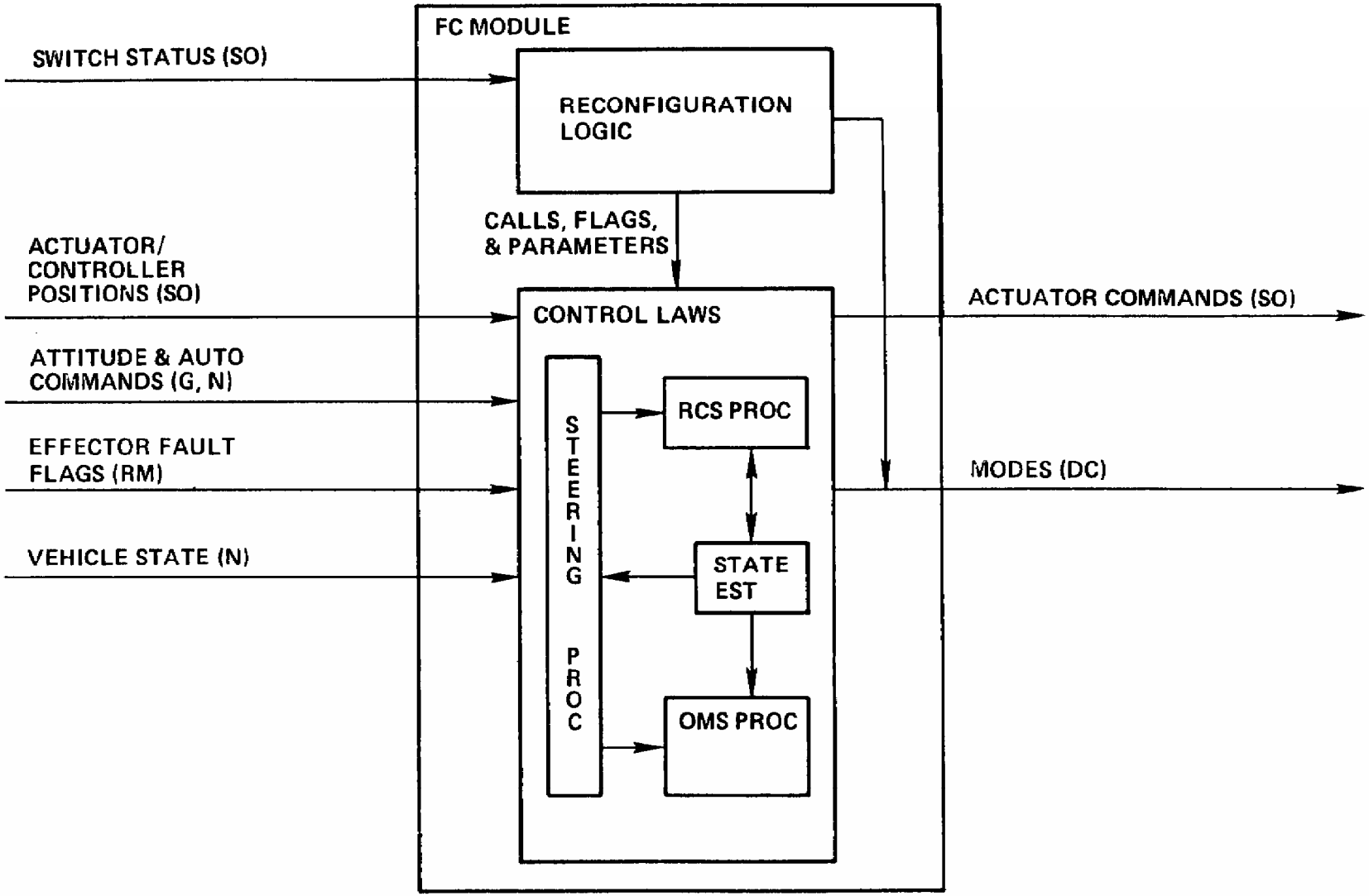
Basic Structure and Interfaces of the On-Orbit DAP



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Topics of Discussion

- Overview
- **The FCS actuators and sensors**
  - **RCS/OMS pods**
  - **RCS details**
  - **OMS details**
  - **Sensor characteristics**
- Summary of the DAP
- Electronic stringing
- Cockpit views

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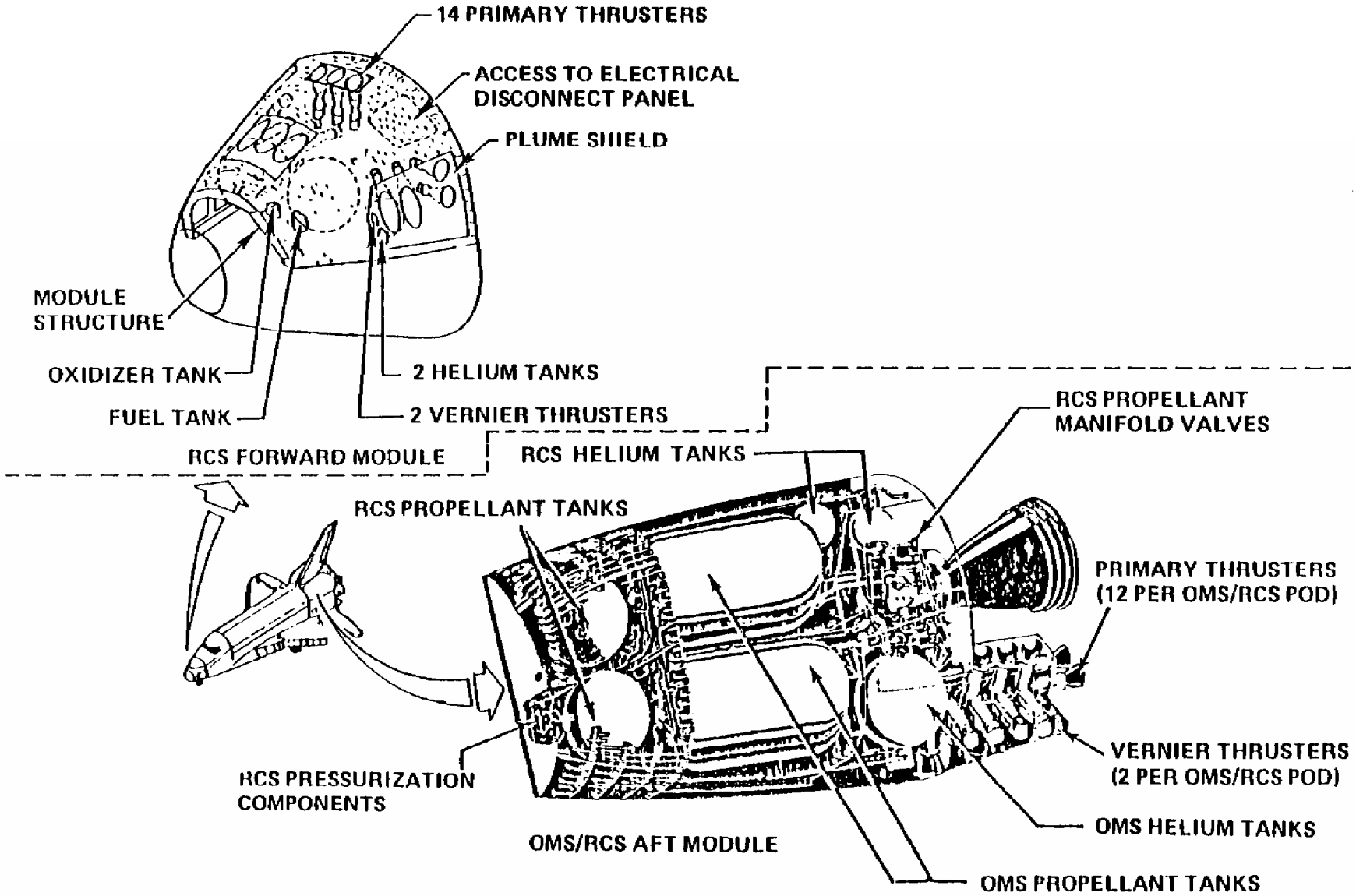
RCS and OMS Pods



(FROM JSC-08934 Vol. I Rev B)

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RCS Hardware Characteristics

- There are 44 stationary, hypergolic liquid bipropellant thrusters on the orbiter
  - 38 PRCS jets
  - 6 VRCS jets
- The minimum on time is 80 ms
- A typical RCS propellant load at launch (based on STS-5)
  - Forward: 2,464 lb
  - Aft: 5,424 lb (split between left and right
- Some performance specifications:

	PRCS	VRCS
Thrust (lbf)	870	24
Specific Impulse (s)	280	265
Duty Cycle Life	20,000	500,000
On-Time Life (s)	12,800	125,000

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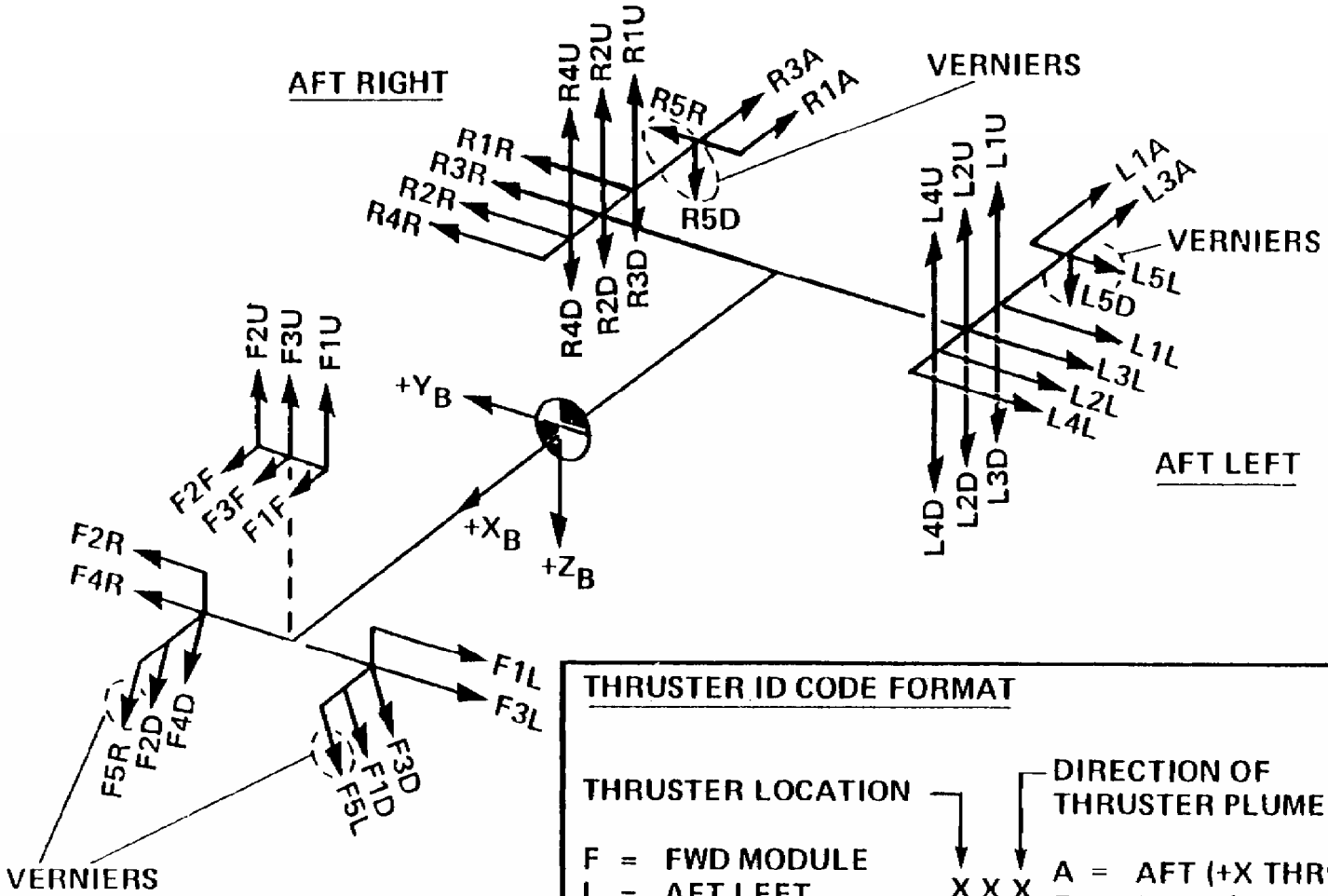
RCS Jet Locations and Plume Directions



(Derived from STS 81-0009)

THRUSTER ID CODE FORMAT

THRUSTER LOCATION — DIRECTION OF THRUSTER PLUME

X X X

F = FWD MODULE
L = AFT LEFT
R = AFT RIGHT
PROPELLANT MANIFOLD NUMBERS (1 through 5)

A = AFT (+X THRUST)
F = FORE (-X THRUST)
L = LEFT (+Y THRUST)
R = RIGHT (-Y THRUST)
U = UP (+Z THRUST)
D = DOWN (-Z THRUST)

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Some OMS Hardware Characteristics

- There are 2 hypergolic, liquid bipropellant OMS engines
- The minimum burn time is 2 seconds
- Typical launch propellant load for both pods
  - Minimum: 10,800 lb (43% full)
  - STS-5: 19,400 lb
  - Maximum: 25,120 lb
- Some performance properties:
  - Thrust per engine: 6,000 lbf
  - Specific Impulse: 313 s
- Gimbal actuator motion limits

	Hardware Limits (deg)	Software Limits (deg)
Pitch	+/- 6.00	+/- 5.89
Yaw	+/- 7.00	+/- 6.44

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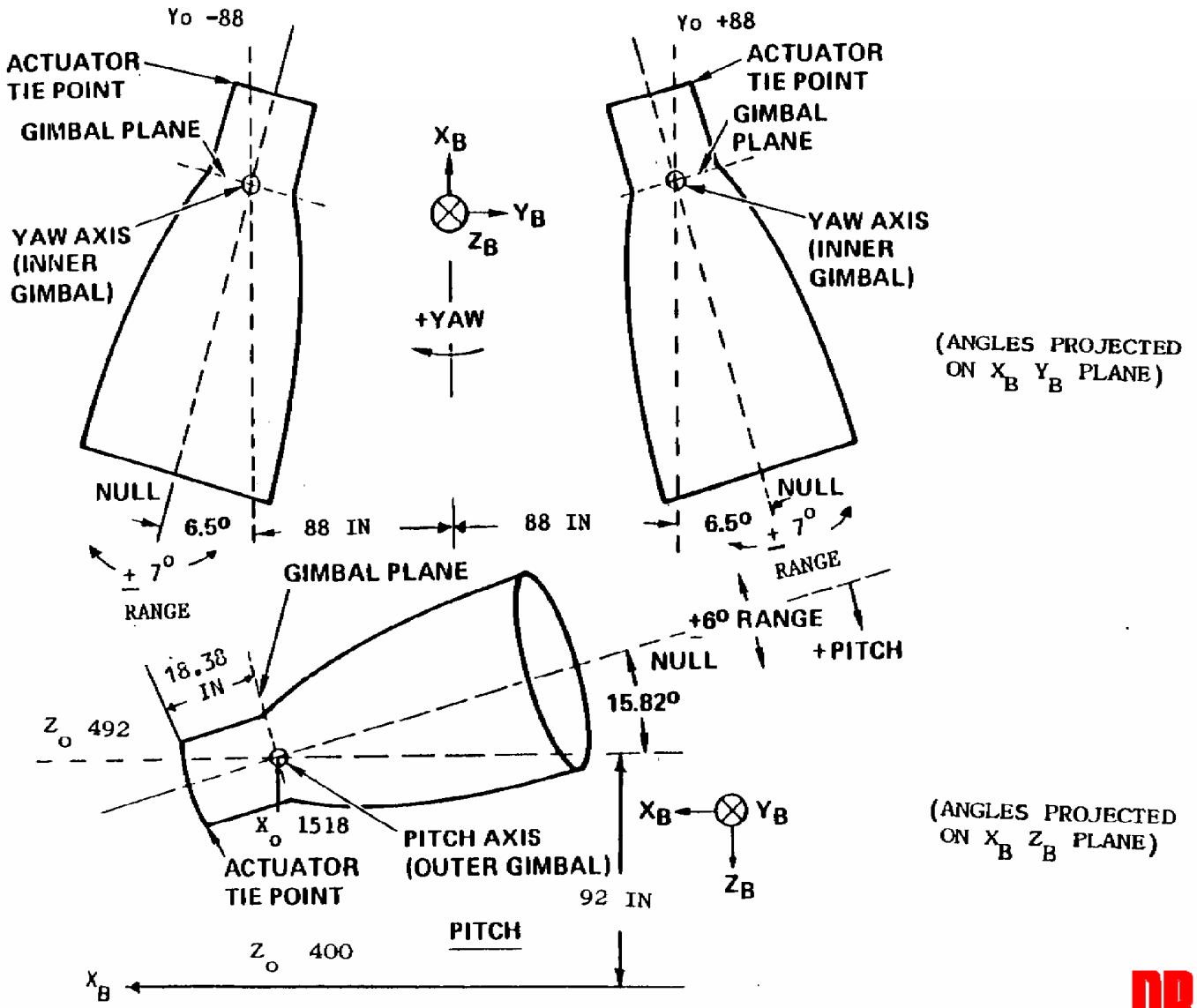
OMS Gimbal Locations and Motions



(FROM STS 82-0626)

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Sensor Characteristics

- IMUs
  - 3 units
  - 0-360 deg/axis attitude range (~20 arcsec quanta)
  - +/- 6-g acceleration range (~1 cm/s^2 quanta)
- RGAs
  - 4 units
  - 3 single degree of freedom gyros per unit
  - +/- 40 deg/s rate range for roll (~0.08 deg/s quanta)
  - +/- 20 deg/s rate range for pitch and yaw (~0.04 deg/s quanta)
  - 1-σ noise: ~2/3 quanta

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Topics of Discussion

- Overview
- The FCS actuators and sensors
- **Summary of the DAP**
  - **DAP functionality**
  - **DAP sensor data paths**
  - **Simplified DAP block diagrams**
  - **The on-orbit state estimator**
  - **The RCS processor**
  - **The OMS Thrust Vector Control (TVC) processor**
  - **RCS wrap-around to the TVC processor**
  - **Some RCS rotation maneuver modes**
- Electronic stringing
- Cockpit views

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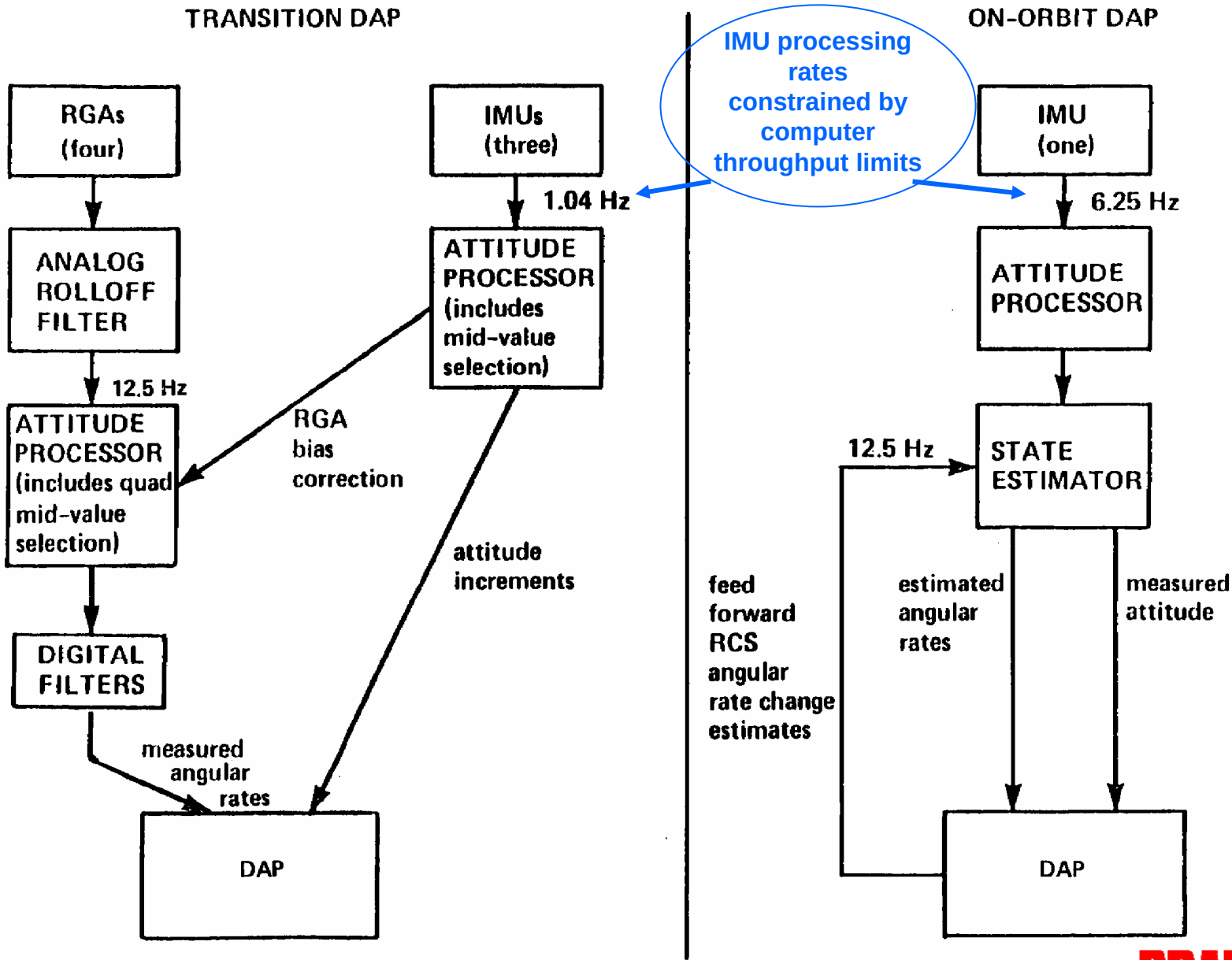
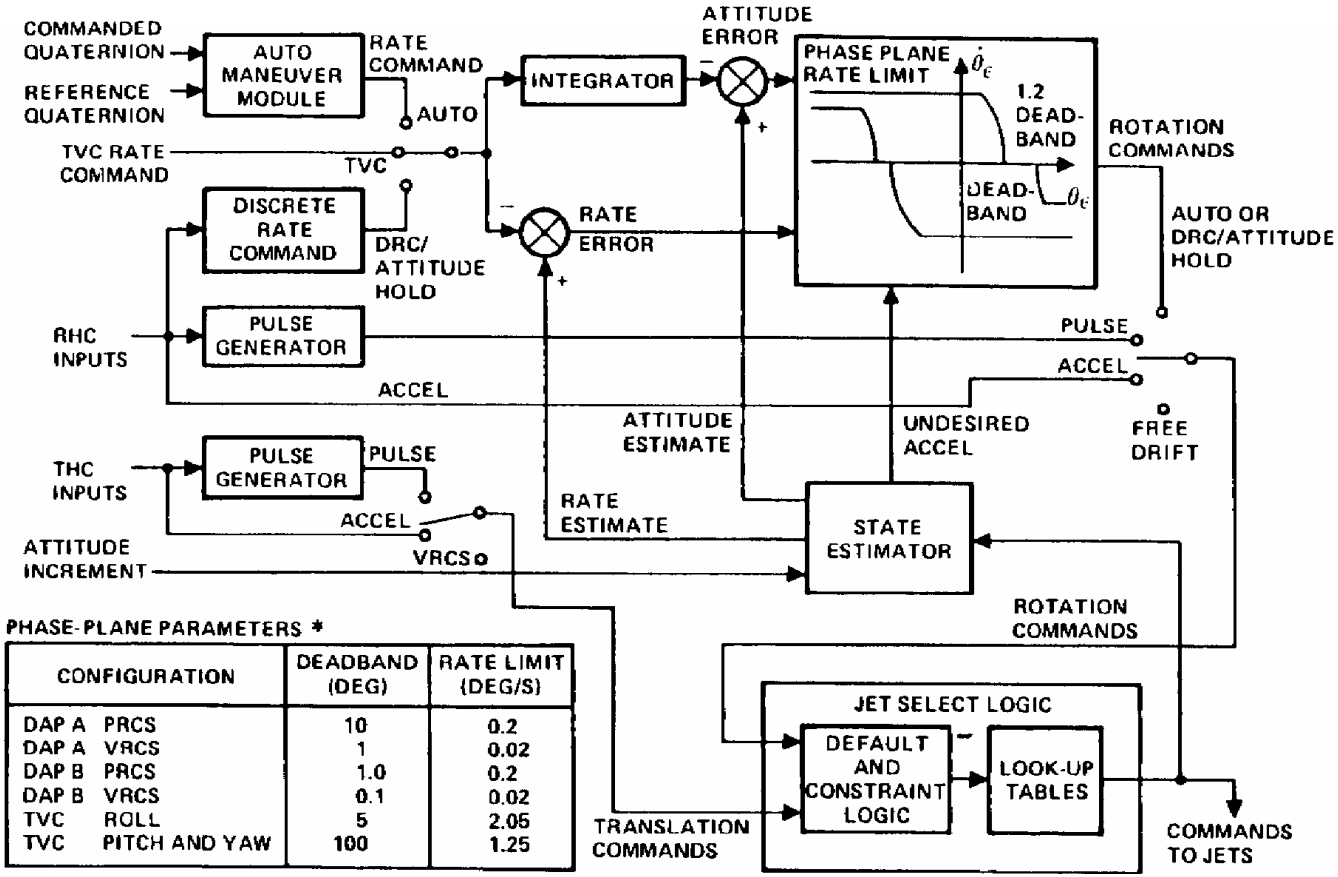
DAP Functionality

Function	Transition DAP Features	On-Orbit DAP Features
State Measurement	Use rate gyros with IMU correction	Use state estimator with IMU data only
RCS Processor	• PRCS jet selection • Rate gyro noise suppression in phase plane switching logic	• PRCS and VRCS jet selection • Estimated disturbance acceleration correction in phase plane switching logic • Efficient use of inter-axis rotation coupling of VRCS jets • Accommodation to crew control parameter changes through interactive cockpit displays
OMS Processor	• Allow two-engine or one-engine burns • Include thrust vector attitude control • Allow RCS wrap around attitude control	Same as Transition
Steering Processor	• OMS burn automatic steering • Translation acceleration mode • Rotation discrete rate, pulse, and hand controller hard stop acceleration modes • Automatic maneuver mode • Automatic ET separation	• OMS burn automatic steering • Translation acceleration and pulse modes • Rotation discrete rate, pulse, and acceleration modes • Automatic maneuver/track mode • Local Vertical/Local Horizontal (LVLH) discrete rate mode

DAP Sensor Data Paths



Simplified On-Orbit RCS DAP



PHASE-PLANE PARAMETERS *

CONFIGURATION	DEADBAND (DEG)	RATE LIMIT (DEG/S)
DAP A PRCS	10	0.2
DAP A VRCS	1	0.02
DAP B PRCS	1.0	0.2
DAP B VRCS	0.1	0.02
TVC ROLL	5	2.05
TVC PITCH AND YAW	100	1.25

(FROM AIAA 82-1576)

* FOR STS-1

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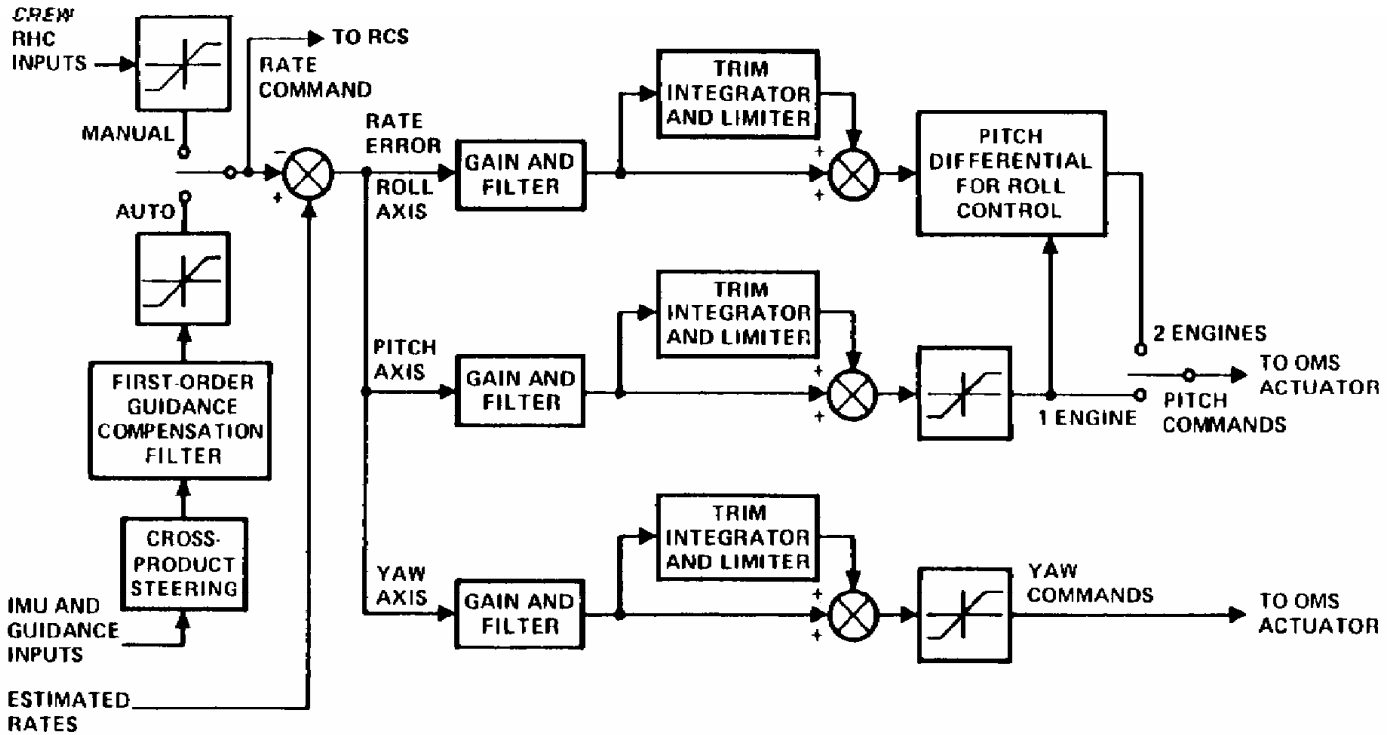
Simplified On-Orbit OMS DAP



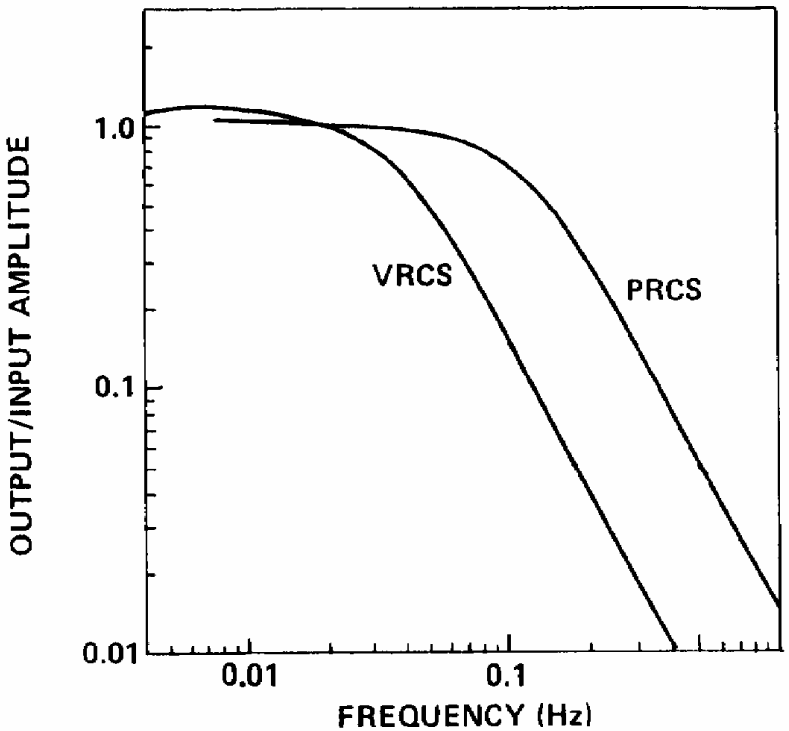
(FROM AIAA 82-1576)

On-Orbit State Estimator Summary

- Objectives
  - Maintain an estimate of vehicle rotation rates
  - Accurately determine slowly varying disturbance accelerations
  - Only rely on rotational position data from the IMU
  - Suppress IMU noise, quantization effects, and high-frequency flexure
  - Facilitate efficient DAP attitude control propellant usage

- Estimator design features
  - Low rate filter that incorporates measurements
    - IMU input data rate limited by processor throughput constraints
  - High rate filter that extrapolates rates and accounts for projected (fed forward) RCS-derived rate changes
  - Applies constant-gain Kalman filter
    - IMU back-differenced during OMS burns
    - Gains set differently for PRCS and VRCS usage

State Estimator Frequency Response



(FROM CSDL SSV 82-6)

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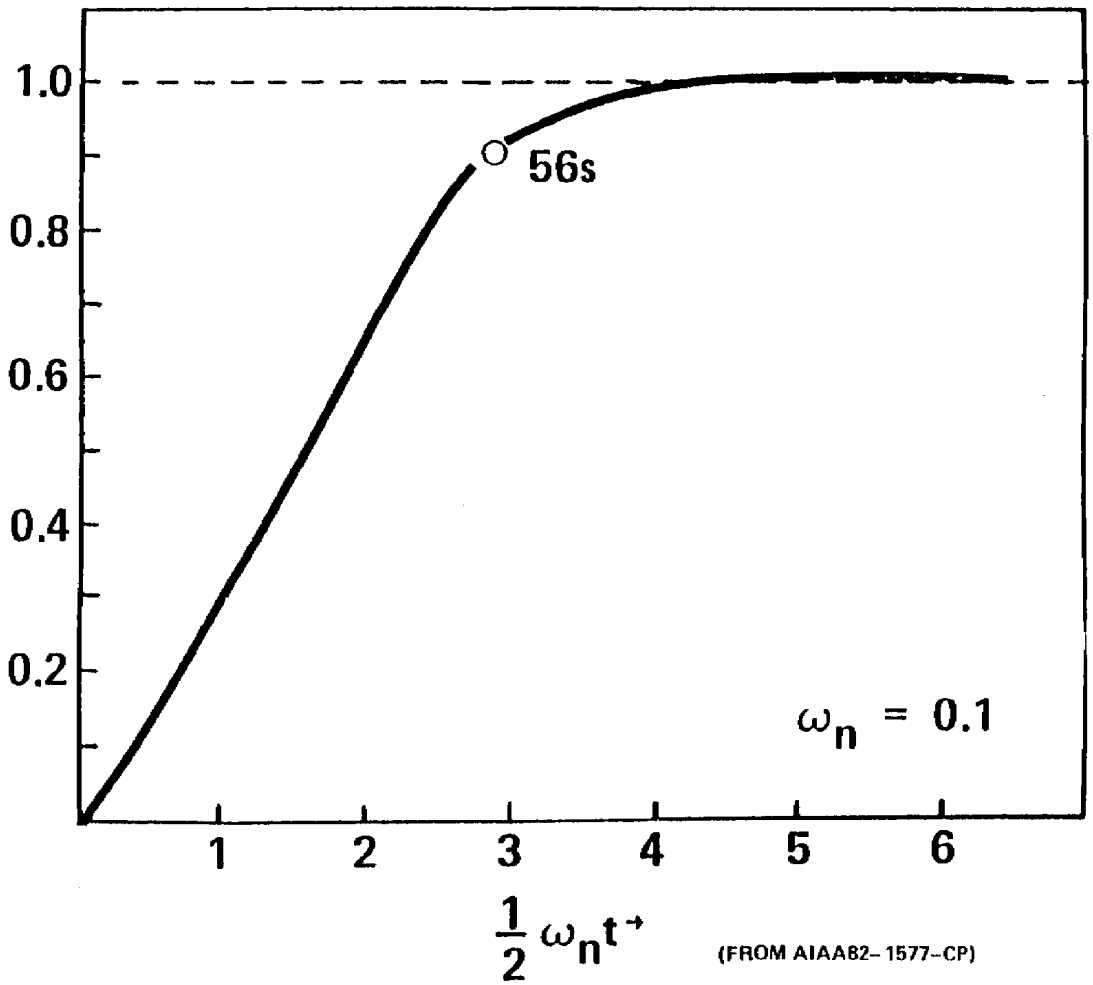
State Estimator Disturbance Acceleration Step Response



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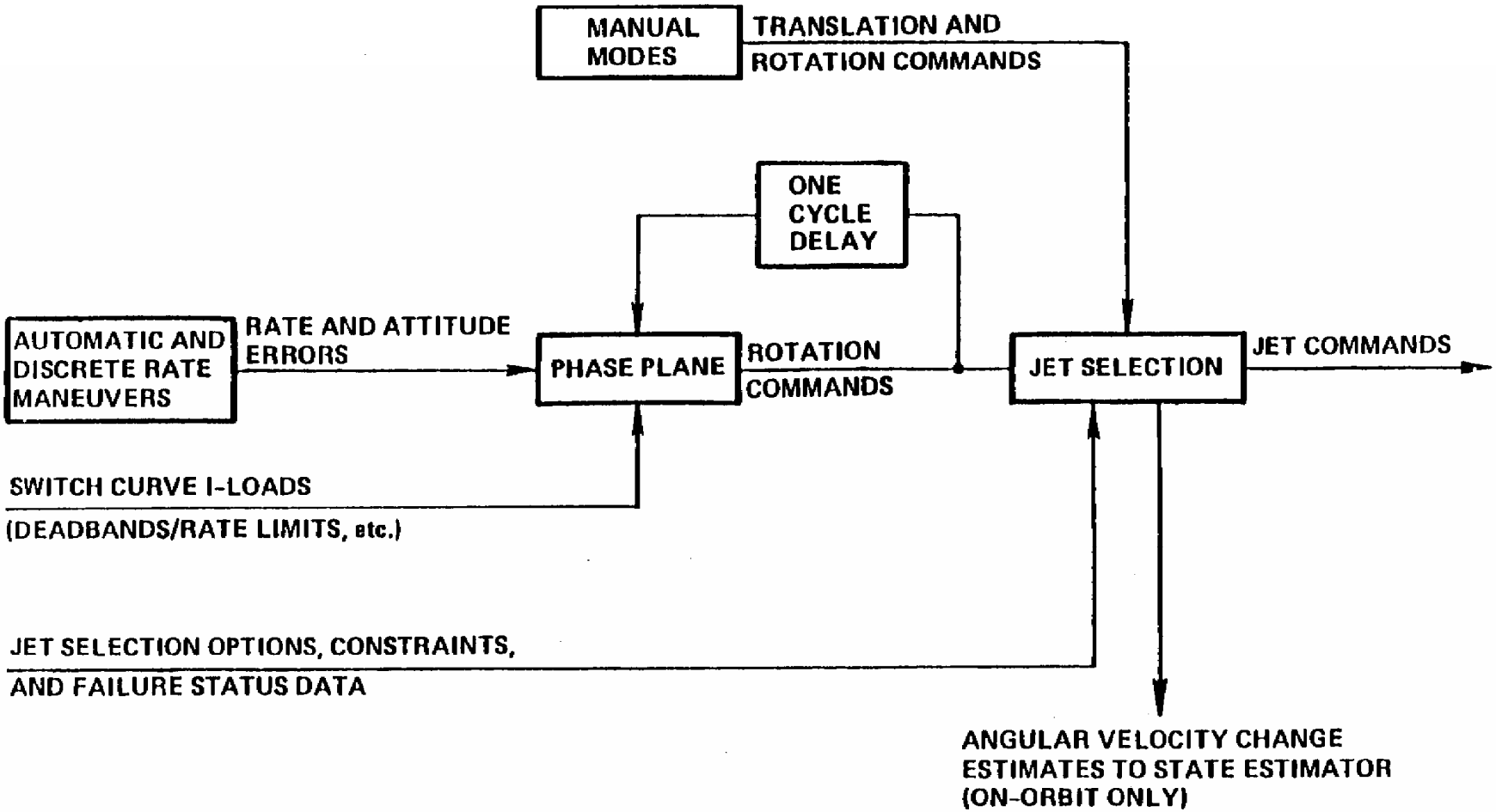
RCS Processor Summary

- Phase-plane (attitude error vs. rate error) switching logic used to generate rotation commands for the jet selection logic
- Jet selection logic picks thrusters to respond to the input combination of translation and rotation commands
  - Allows selection of PRCS or VRCS
    - VRCS jets are only used on-orbit
  - Accounts for numerous constraints and conditions
    - Detected jet failures
    - Jet plume restrictions on nearby spacecraft
    - Limits on simultaneous jet firings from a single tank
  - Chooses jet “couples”, but with on-orbit option for forward/aft jet usage preferences (for propellant use balancing)
  - Has multiple translation acceleration levels in the Z axis
    - Nominal (3 +Z jets / 4 –Z jets)
    - High (9 +Z jets for rendezvous braking / 10 –Z jets for ET separation)
    - Low (only for +Z translation; applies Z-axis thrust coupling from combined +/- X-axis jet firings)
      - Used for plume impingement restricted proximity operations with another vehicle

RCS Processor Top-Level Architecture



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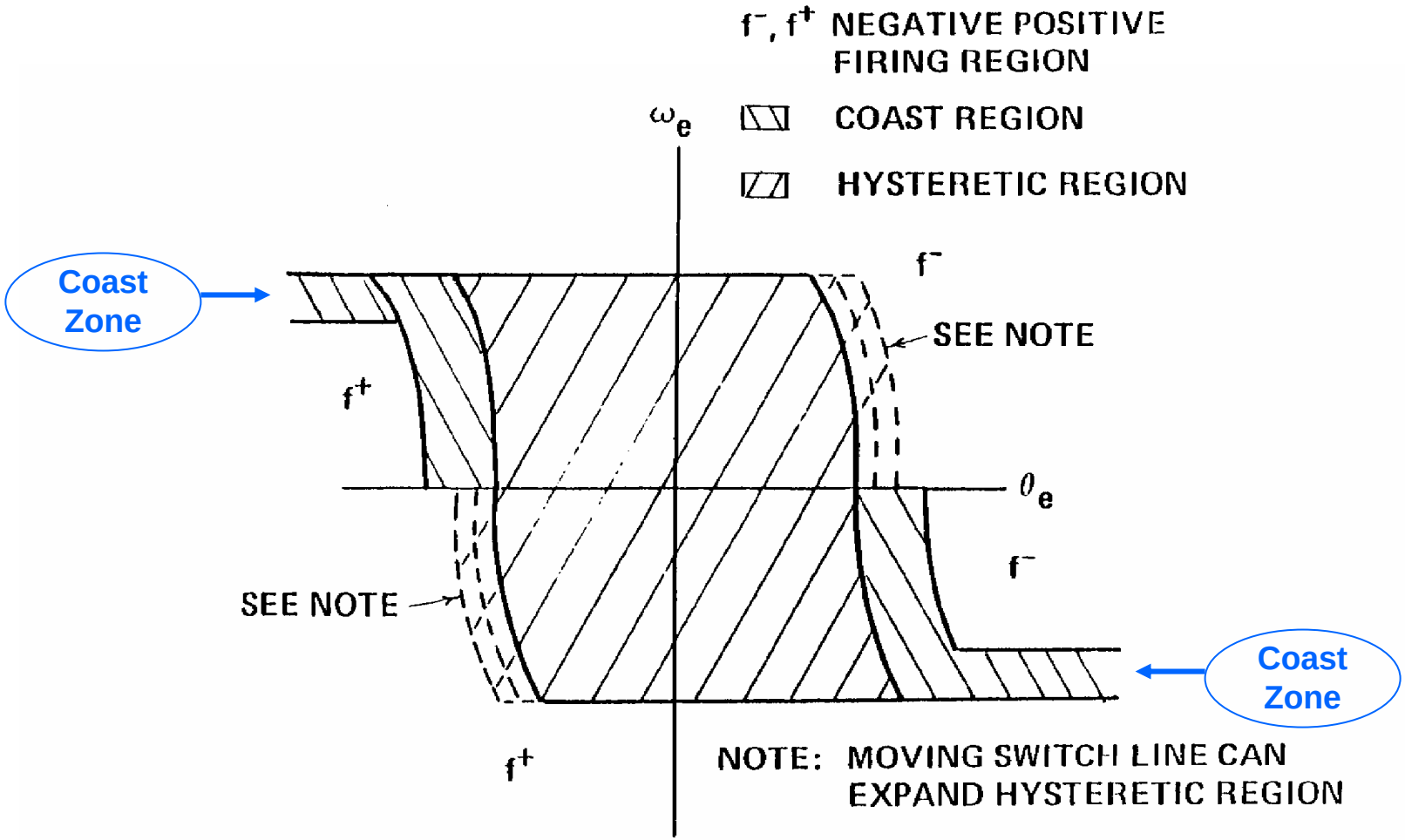
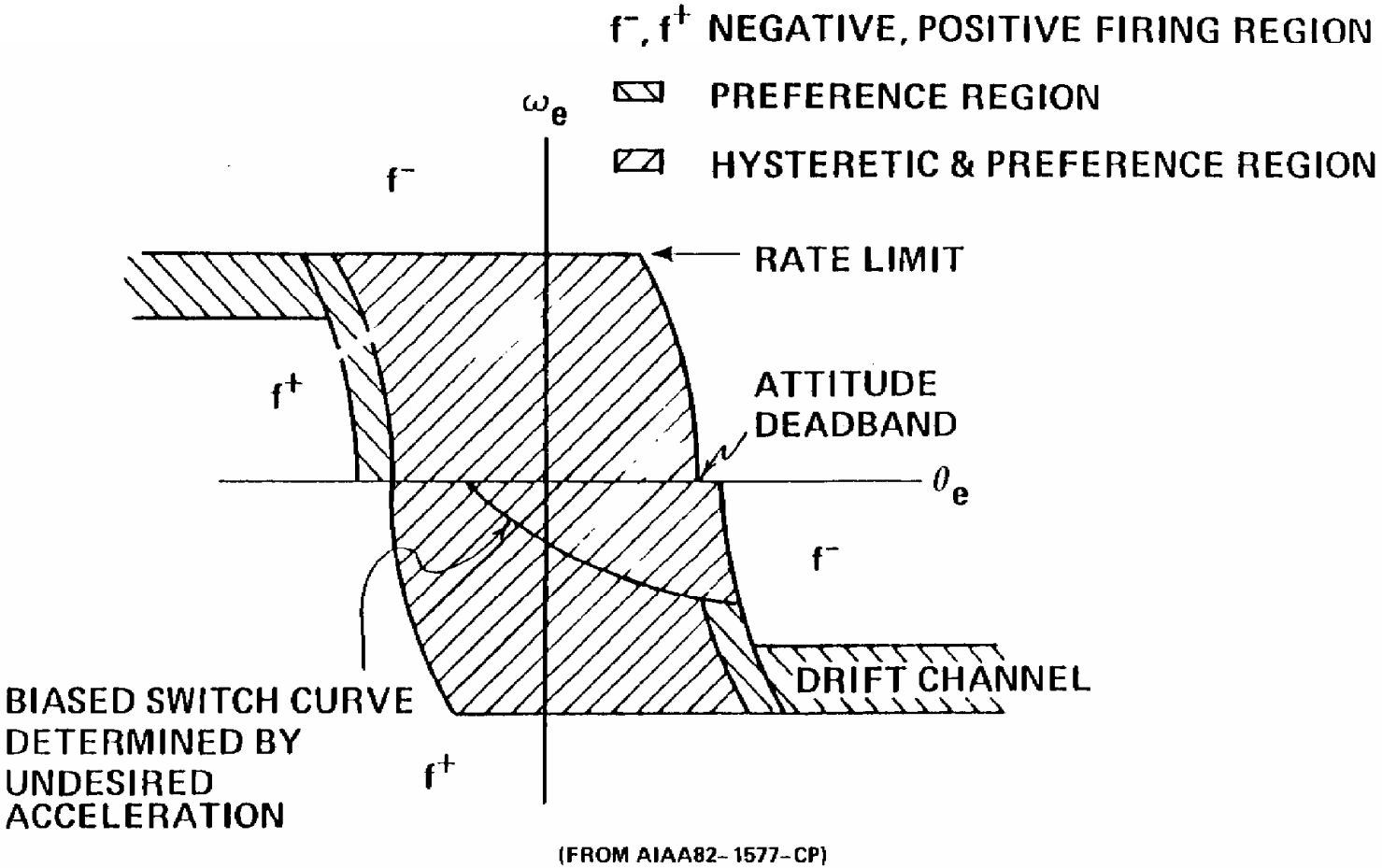
Phase Plane Principles

- Each vehicle body rotation axis is controlled separately with its own phase plane
- Switch lines are shaped by expected control torques and disturbances
  - Attitude dead band switch lines are shaped by expected accelerations in order to contain phase plane trajectories when jets fire
  - Transition DAP attitude dead band switch lines can be incrementally increased several times to protect against rate gyro quantization noise (to improve propellant usage efficiency and reduce duty cycles)
  - On-orbit DAP target rate switch line is biased to compensate for estimated disturbance accelerations
- The phase plane origin is shifted:
  - To center on targeted maneuver rates
  - To track the targeted attitude position
- Attitude error coast zones (or “drift channels”) permit large attitude error corrections with low propellant consumption

Transition DAP Phase Plane Regions



On-Orbit DAP Phase Plane Regions



(FROM AIAA82-1577-CP)

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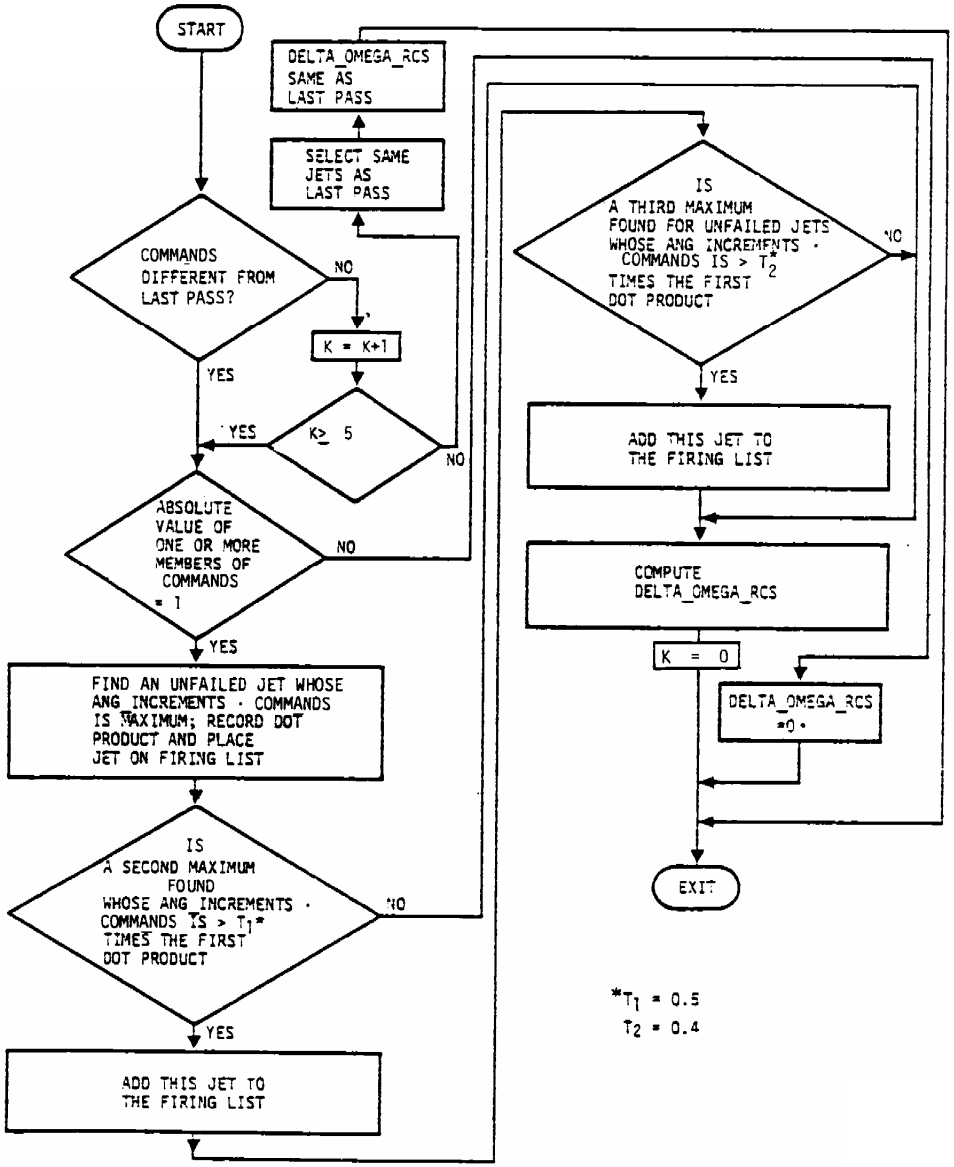
Jet Selection Principles

- PRCS and VRCS jets generally do not operate simultaneously
  - A software upgrade in the 1990s provided the only exception: A single PRCS jet can be used to replace a failed VRCS jet (since the VRCS jets are not fault tolerant)
- PRCS jets are selected based on a table lookup algorithm
  - X-axis jets control X translation (and plume restricted +Z translation)
  - Y-axis jets control Y translation and yaw rotation
  - Z-axis jets control Z translation as well as pitch and roll rotation
- VRCS jets are only used on-orbit
  - They provide rotation control, using a dot-product algorithm based on a command vector and expected thruster acceleration vectors
    - Responds to commanded axis (axes) while biasing thruster selection to correct errors in uncommanded axes
    - If commands do not change, selected jets remain constant for 5 DAP cycles to limit thruster duty cycles
    - Alternate expected thruster acceleration vector sets are available to account for large controlled-system mass property changes (e.g., free orbiter flight vs. extended payload or docked operations)
  - An upgrade was provided in the 1990s to also enable use for gentle Space Station and Space Telescope reboost
    - applies the four VRCS thrusters that fire into the –Z direction

Vernier Jet Selection Simplified Flow Chart



*T_1 = 0.5
T_2 = 0.4

(DERIVED FROM STS 81-0009)

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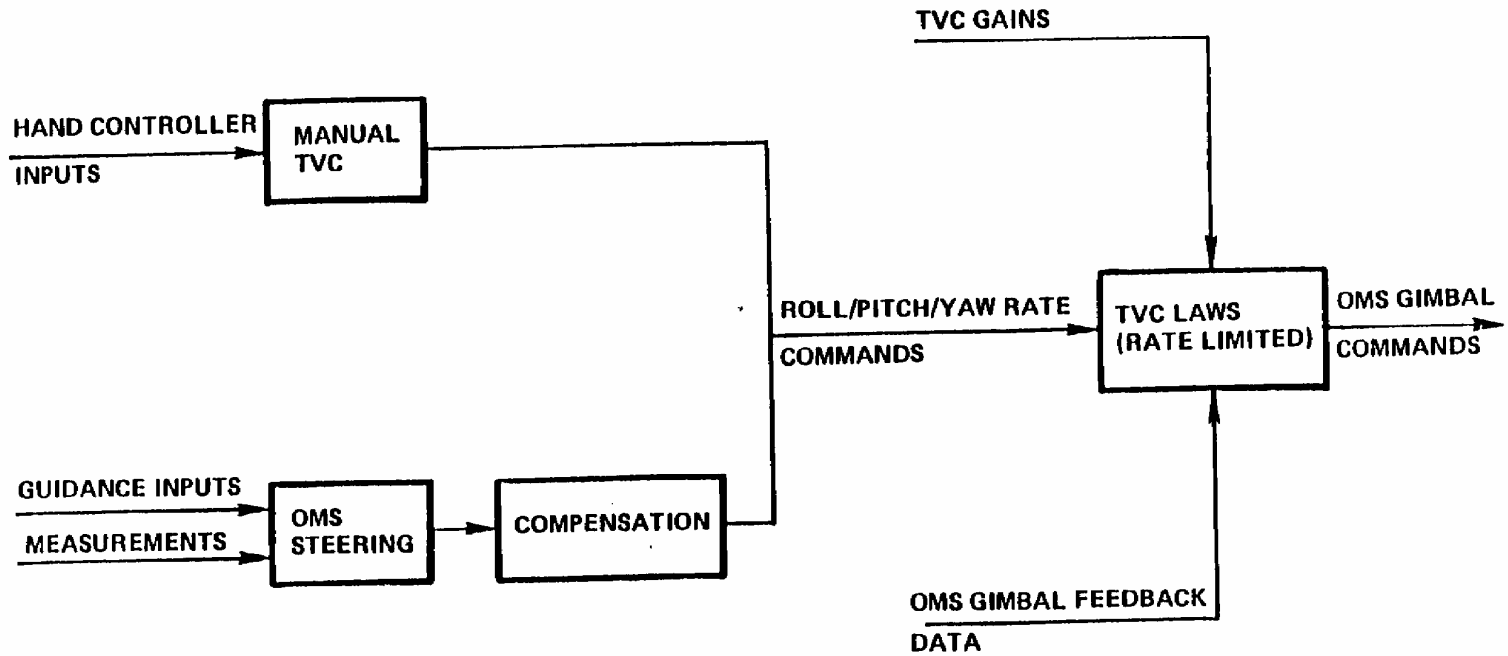
TVC Processor Overview

- Automatic OMS steering generates vehicle rotation rate commands
  - Based on a cross product of the guidance-commanded thrust direction and the sensed vehicle velocity change
  - A compensation module filters the steering and applies a 2/deg/s/axis steering rate command limit

- Manual TVC generates rate commands proportional to hand controller deflection
  - TVC rate commands are limited to 2 deg/s/axis
  - Moving the hand controller to its hard stop induces PRCS wrap-around of the TVC with no rate limit

- TVC laws command OMS gimbals to control vehicle rotation
  - Provide three axis rotation control during two engine burns
  - Provide pitch and yaw control during one engine burns
    - Roll rotation is controlled by the PRCS

TVC Processor Simplified Block Diagram



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OMS TVC Inner Loop Design Considerations

- Tolerance to the following disturbances and errors is needed:
  - OMS engine thrust direction offset due to gimbal misalignment
  - Vehicle rotation state errors at ignition
  - Failures during OMS burns (i.e., OMS engine; OMS actuator; RCS jets)
  - Effects of dumping the main engine residual propellant
  - Sensor noise and bias
- Margins are needed for the following system dynamics perturbation effects:
  - Propellant slosh
  - Orbiter flexure
  - Actuator nonlinearities
  - Variable sampling rate effects

OMS TVC Pitch/Yaw Design Characteristics

Design Characteristic	High Bandwidth Design (STS-1 through STS-11)	Low Bandwidth Design (STS-12 and After)
Crossover Frequency (rad/s)	0.88	0.4
Phase Margin (deg)	56	60
Gain Margin (dB)	8	11
Slosh Phase Margin at 1.5 rad/s (deg)	36	10
Attenuation at 20 rad/s - 30% below first bending mode of 29.4 rad/s (dB)	60	~100
Actuator Activity (on-off cycles/s)	~1.6	0.4

- Initial flight data showed the OMS gimbal actuator life was being shortened by actuator motor overheating due to high bandwidth commanded control response
- A lower bandwidth design change was implemented to reduce OMS actuator activity

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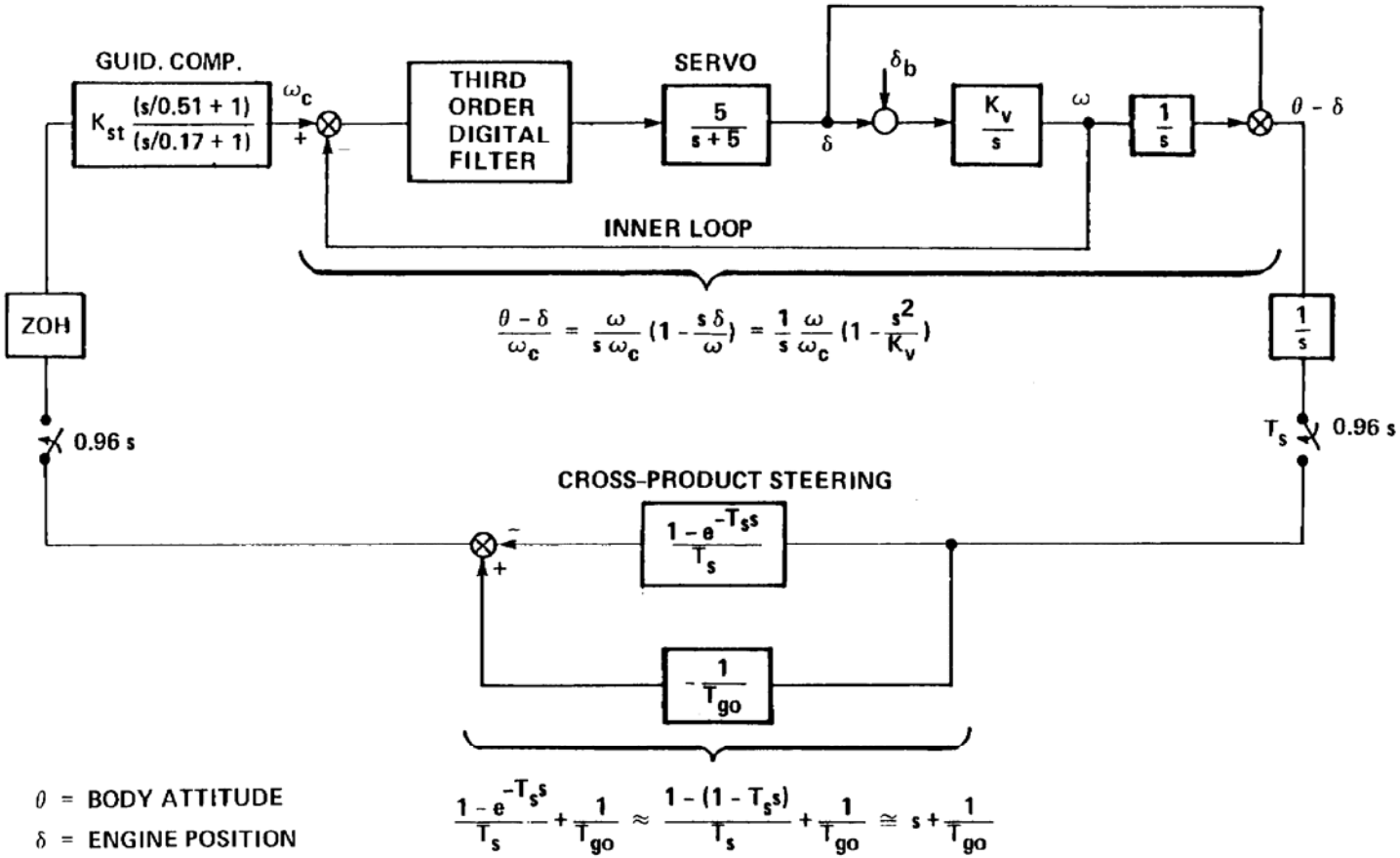
TVC Processor Outer Loop



θ = BODY ATTITUDE

δ = ENGINE POSITION

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RCS Wrap Around to the TVC Processor

- PRCS rotation control can be called upon to assist the OMS TVC on a per-axis basis under the following conditions
  - Roll axis control for single OMS engine burns
    - TVC controls the pitch/yaw axes
    - PRCS roll control applies a wrap-around dead band and rate limit
  - The hand controller soft stop is exceeded
  - The limits in the table below are exceeded
    - STS-12+ changes were made to reduce the chances that adverse coupling ("force fights") between the OMS TVC and PRCS wrap-around control laws

	Rate Limit (deg/s)		Dead Band (deg)	
	Initial Threshold	STS-12+	Initial Threshold	STS-12+
Roll	2.05	2.05	5.0	5.0
Pitch	1.25	2.05	100.0	10.0
Yaw	1.25	2.05	100.0	10.0

RCS Automatic Maneuver/Track Mode (on-orbit only)

- Provides maneuver or track options selected and monitored through a universal pointing display
  - Target attitude is controlled by the selected option, with a time-dependent attitude in track mode
- A maneuver rate Eigen vector is computed from a maneuver quaternion (derived by comparison of the current vs target attitude)
  - Per-axis maneuver components can bias the phase plane rate origins
    - Done if the total attitude error exceeds twice the per-axis dead band plus a deceleration bias
    - The phase plane rate origins are held stationary if the total attitude error is less that the per-axis dead band plus the same bias
    - The maneuver rate effect on the phase plane rate origin is subject to hysteresis between large and small regions
    - The phase plane attitude origins are translated at the current per-axis desired maneuver rate

Manual RCS Modes

- Translation
  - Direct control of autopilot achieved by hand controller deflection
  - Guidance can be accomplished by crew monitoring of displayed velocity changes
  - Available options:
    - Acceleration mode (in the transition and on-orbit DAPs)
    - Controlled pulse mode (only on-orbit)
- Rotation
  - Direct control of the autopilot achieved by hand controller deflection (though possibly through phase plane and state estimation algorithms)
  - Automatic, discrete rate control in response to manual commands is possible relative to:
    - Inertial references (in the transition and on-orbit DAPs)
    - LVLH references (only on-orbit)
  - Open loop manual control is available with the rotation state monitored through dedicated displays (in the transition and on-orbit DAPs)
    - An acceleration mode
    - Controlled pulse modes

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Topics of Discussion

- Overview
- The FCS actuators and sensors
- Summary of the DAP
- ➢ **Electronic stringing**
  - **Stringing overview**
  - **RCS jet stringing**
  - **OMS valve stringing**
  - **Effects of string failures**
- Cockpit views

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Electronic Stringing Overview

- Four independent electronic strings control all FCS data paths to/from sensors and actuators
  - Each string has one forward and one aft Multiplexor/Demultiplexor (MDM)
  - Each sensor or actuator component is uniquely attached to one string
  - Each string can be latched to any GPC
  - No string can be latched to more than one GPC at a time
- Each component on each electronic string has a unique lash-up to power buses
  - Three independent power buses supply all FCS sensors, actuators, and data processors

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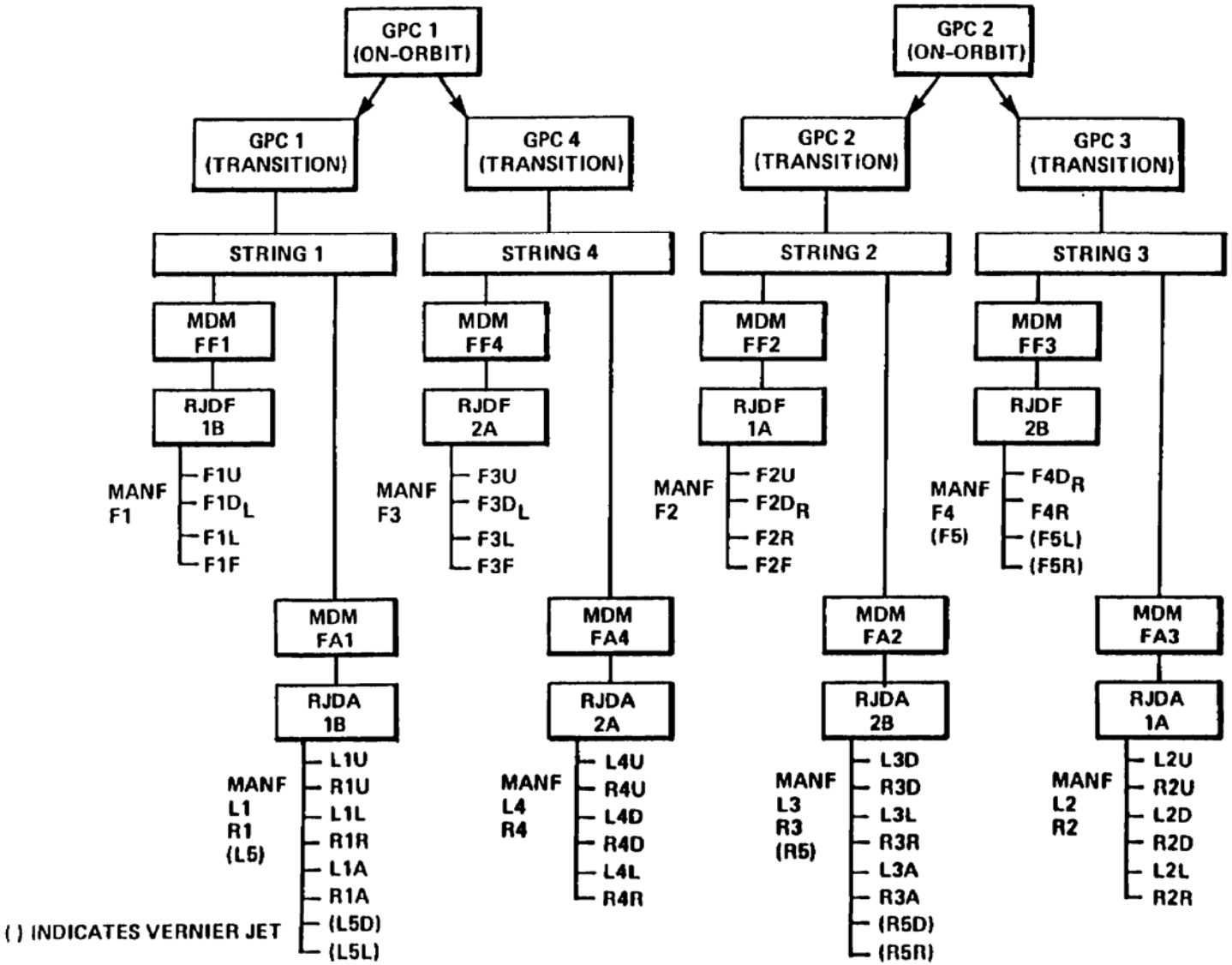
GPC/Reaction Jet Driver (RJD) Stringing



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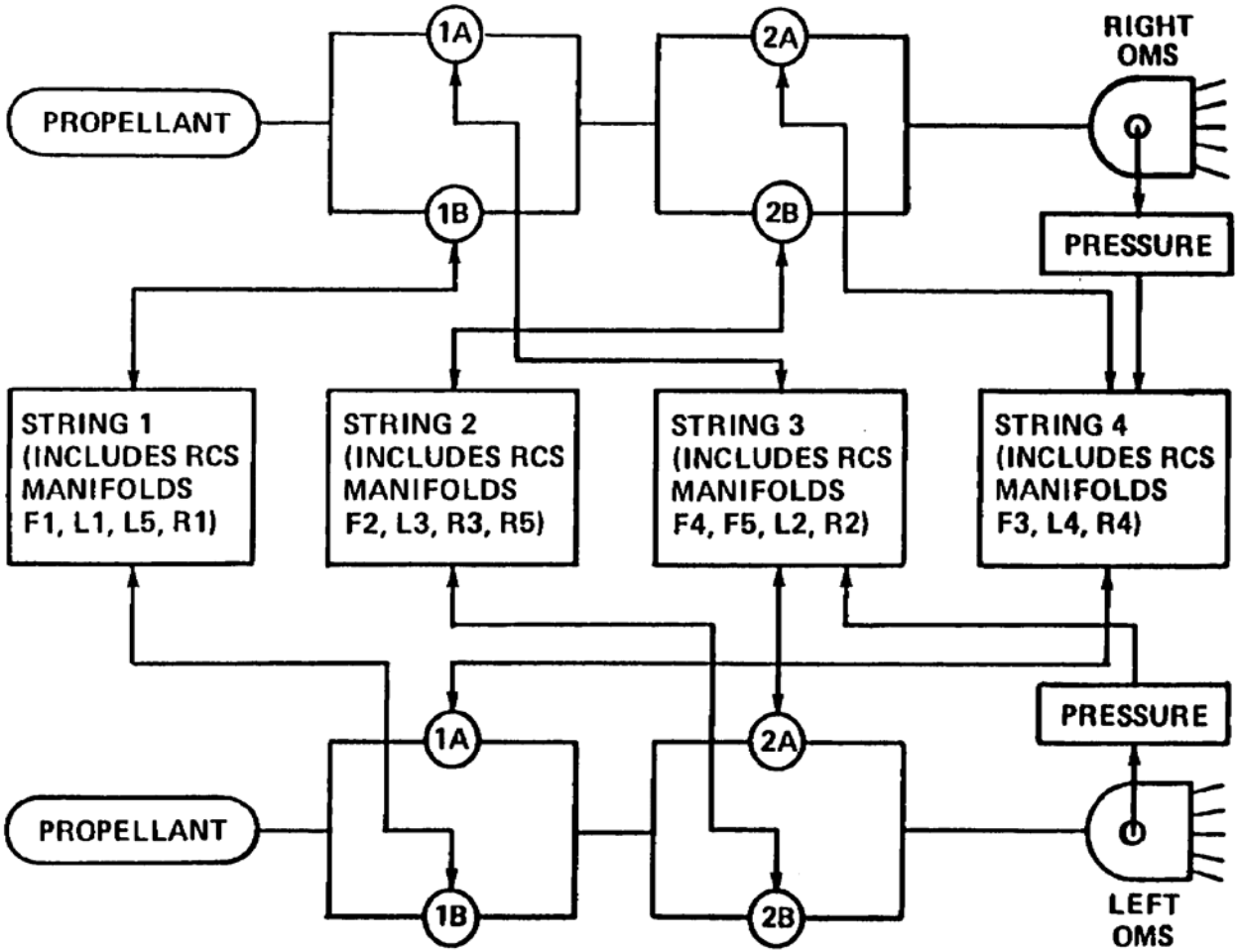
Electronic Stringing of OMS Valves and Sensors



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Effects of Electronic Failures (p. 1 of 2)

- Each string affects many subsystems
  - One PRCS jet manifold per pod
  - One VRCS manifold (on three out of four strings)
  - One RGA
  - One propellant valve per OMS engine
  - One IMU (on three out of four strings)
  - One OMS chamber pressure sensor (on two out of four strings)
- One GPC can affect any number of electronic strings
  - One string per GPC nominally in the transition DAP
  - Two strings per GPC nominally in the on-orbit DAP
  - Extra strings can be affected following reconfiguration from previous GPC failures
- Loss of one string has a few manageable effects
  - May prevent VRCS jet use
  - PRCS jet translation authority is degraded
  - One set of OMS actuators may freeze (but the actuators are redundant)

Effects of Electronic Failures (p. 2 of 2)

- Loss of two stings without reconfiguration can have multiple, severe effects (beyond the list above)
  - Some RCS translation control may be lost, and rotation control is degraded
  - One OMS engine may lose all TVC control
  - If MDMs are not reset
    - One OMS engine may require manual shutdown
      - When one valve per propellant feed line is left open: could result in an overburn
    - One OMS engine may fail
      - When two valves in one propellant-feed-line loop close
- In the on-orbit phase, the navigation state can temporarily be lost
  - Typically, only one IMU is used on-orbit to conserve power

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Topics of Discussion

- Overview
- The FCS actuators and sensors
- Summary of the DAP
- Electronic stringing
- **Cockpit views**
  - **Original cockpit**
  - **Upgraded cockpit**

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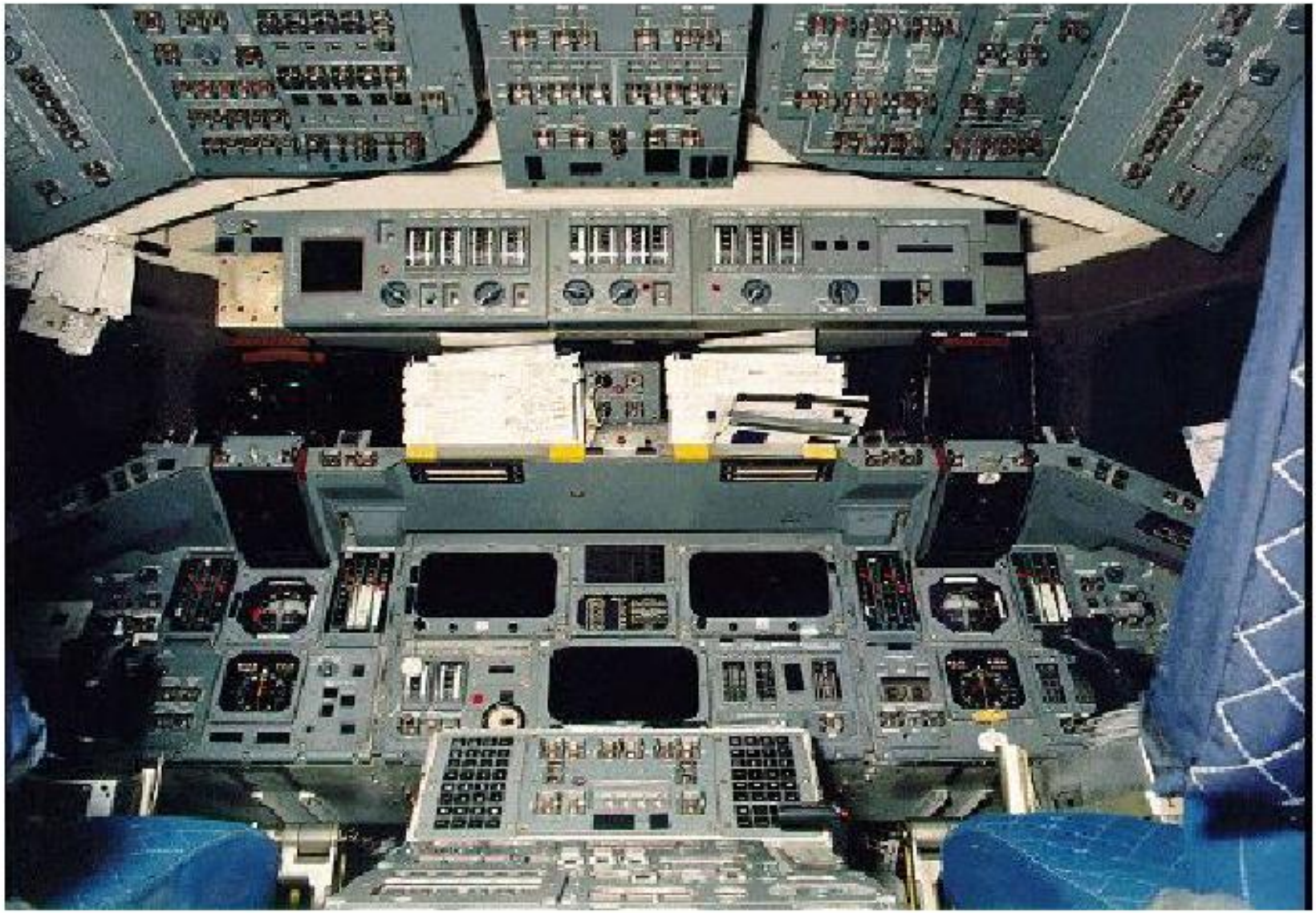
Original Cockpit



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Upgraded Cockpit

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