

## Space Flight Operations Contract

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# Entry Digital Autopilot Workbook

**ENTRY DAP 21002**

August 24, 2004

Contract NAS9-20000

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**Entry Digital Autopilot Workbook**  
**ENTRY DAP 21002**

Prepared by

*Original approval obtained*

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Mark A. Veile, Book Manager  
USA/Control/Propulsion Department

Approved by

*Original approval obtained*

---

Michael R. Sterling, Manager  
USA/Control/Propulsion Department

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## PREFACE

The content of this document was provided by the Control/Propulsion Department, Space Flight Training Division, Mission Operations Directorate (MOD), Lyndon B. Johnson Space Center (JSC), National Aeronautics and Space Administration (NASA). Technical documentation support was provided by Integrated Documentation Services (IDS), Hernandez Engineering, Inc. Any questions concerning this workbook or any recommendations should be directed to the book manager.

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If this workbook is being read as part of a formal syllabus, the reader should complete the training materials evaluation form at the end of the document. The evaluation form does not need to be signed.

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## 1.0 DIGITAL AUTOPILOT SYSTEM

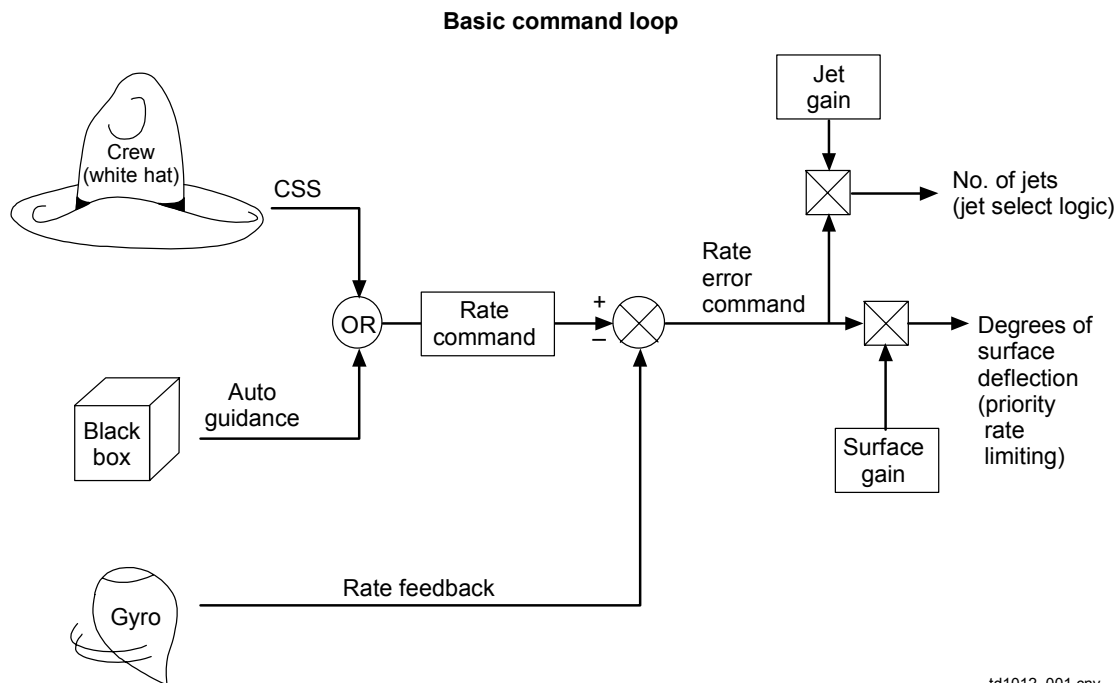
### 1.1 OBJECTIVES

At the end of this section, the student will be able to

- State the two control systems that the entry Digital Autopilot (DAP) commands.
- State the two ways entry DAP is provided with command rates.
- State the input data necessary for the determination of control requirements.

### 1.2 INTRODUCTION

The entry DAP, also referred to as the aerojet DAP, commands the aerodynamic control surfaces and the Reaction Control System (RCS) jets to provide vehicle trim, coordinated flight maneuvers, energy modulation, and steering on the runway. The entry DAP is a rate command system, with the command rate provided by either the pilot, through Control Stick Steering (CSS), or by automatic guidance (AUTO). The commanded rate is compared to the actual rate (rate feedback), resulting in a rate error. This rate error is multiplied by the appropriate gains to produce RCS jet and/or aerodynamic surface commands to produce the desired rate, reducing the rate error. Figure 1-1 shows a very basic schematic of the entry DAP. Regardless of how complicated succeeding schematics become, they functionally reduce to the schematic shown in Figure 1-1.



**Figure 1-1. Entry DAP job description**

Entry DAP is active in both the Primary Avionics Software System (PASS) and the Backup Flight System (BFS) during Major Mode (MM) 304 and 305 for End of Mission (EOM), Transoceanic Abort Landing (TAL), or Abort Once Around (AOA). Entry DAP is also active during Glide Return to Launch Site (GRTLs) flight in MM602 and MM603.

In both Auto and CSS flight control, entry DAP has both a Baseline and Wraparound flight control mode available in MM304/305. Wraparound DAP is not available in MM602/603. Additionally, alternative flight control modes are available in off-nominal situations. These include No Yaw Jet and Low Gain. These flight control options will be discussed in later chapters.

The shuttle entry DAP has some features that aid its unique flying. Turn coordination is provided so that bank maneuvers are coordinated automatically, without rudder pedal inputs being required, from entry to touchdown. Nose up turn compensation allows for a near constant flight path angle during banked turn maneuvers. Alpha modulation (angle of attack modulation) during bank maneuvers keeps the actual drag acceleration from diverging from the reference drag when rolling through the wings-level attitude. The entry DAP drives the aerodynamic control surfaces to trim the vehicle during flight. The Body Flap (BF) is driven by the entry DAP to trim the vehicle in pitch. This offloads the trim provided by the elevons, allowing elevons to be used for vehicle control. The Speedbrake (SPBK) is used as a pitch trim device at Mach numbers between 10 and 0.95 and provides energy modulation at Mach numbers below 0.95.

The Rotational Hand Controller (RHC) rate trim (pitch and roll “Beep Trim”) and the panel trim switches (roll, pitch, and yaw) provide manual trimming functions. The RHC trim switch can bias the commanded rates by 1.5 deg/sec in pitch (up or down) or 2.5 deg/sec in roll (left or right). Derotation on the runway after landing is accomplished using the RHC pitch trim switch. The roll and pitch panel trim switches command aileron and elevator integrated surface positions. The roll panel trim switch can be used effectively to manually speed up the trimming process on the roll channel. The yaw panel trim switch can be used to bias the lateral acceleration ( $N_y$ ) feedback by as much as  $\pm 0.1$  g.

Automatic Programmed Test Inputs (PTIs), another feature of the entry DAP, are direct commands to the control surfaces or jets (downstream of any gains, biases, or filters) that provide perturbations from which aerodynamic coefficients can be extracted. These are used to expand the orbiter flight envelope and to reduce some variations and uncertainties in the aerodynamic database.

As with any stability augmented control system, certain data are necessary for determining the control requirements. These input data include navigation-derived parameters from the Inertial Measurement Units (IMUs) and the Air Data Transducer Assemblies (ADTAs); body rotational rates from the Rate Gyro Assemblies (RGA); vehicle normal (vertical) and lateral (side force) accelerations measured by the Accelerometer Assembly (AA); control surface position feedback; guidance commands; and past values of surface and jet commands. Figure 1-2 illustrates the required inputs for the entry DAP, as well as the destination of the output parameters.

The cockpit displays for the crew include entry DAP performance information on the Multifunction Electronic Display System (MEDS) Attitude Director Indicators (ADIs), the RCS jet activity lights, and the Surface Position Indicator (SPI).

On the Commander's (CDR) and the Pilot's (PLT) ADIs, the vehicle rates are displayed on the rate pointers, as shown in Figure 1-2. The roll and yaw rates are in the stability axes, while the pitch rate is in the body axis. The ADI rate switch controls the magnitude of the rates displayed. The three switch positions provide low, medium, and high rates with corresponding values of 1, 5, and 10 deg/sec in each axis. The yaw error needle on each ADI displays the sideslip angle (beta,  $\beta$ ) when the dynamic pressure ( $\bar{q}$ ) is low, and when  $\bar{q}$  is greater than 40 pounds per square foot (psf), it displays "scaled  $A_y$ ." This scaled  $A_y$  is the lateral acceleration after compensation for surface deflections, accelerometer location, jet firings, Mach number, angle of attack, and  $\bar{q}$ . Its accuracy is thus dependent on the modeling accuracy of the aerodynamics and sensors. This parameter is correlated to the control authority available from the yaw jets. A full-scale deflection of the yaw needle is equivalent to the lateral acceleration caused by a sideslip angle that would be balanced by the torque because of 2.5 yaw jets.

### **Summary of Entry DAP features**

- a. Entry DAP is active in MM304/305 and MM602/603, in both PASS and BFS.
- b. Baseline and Wraparound DAP modes are available in Auto and CSS (Wrap DAP not available in MM602/603).
- c. Rate command system with primary feedback from orbiter RGAs.
- d. Turn coordination is provided in AUTO and CSS through entry to FLATTURN/rollout (no rudder pedal commands required normally).
- e. Alpha modulation adjusts vehicle drag acceleration during bank maneuvers.
- f. Nose up turn compensation; i.e., pitch rate commanded in bank maneuvers, provided in Terminal Area Energy Management (TAEM) and Approach and Landing (A/L) phases.
- g. Automatic surface trim commands are from forward loop trim integrators.
- h. BF drives to trim vehicle such that elevons and SPBK may follow programmed schedules.
- i. Surface and jet automatic PTIs are for aero coefficient data reduction.

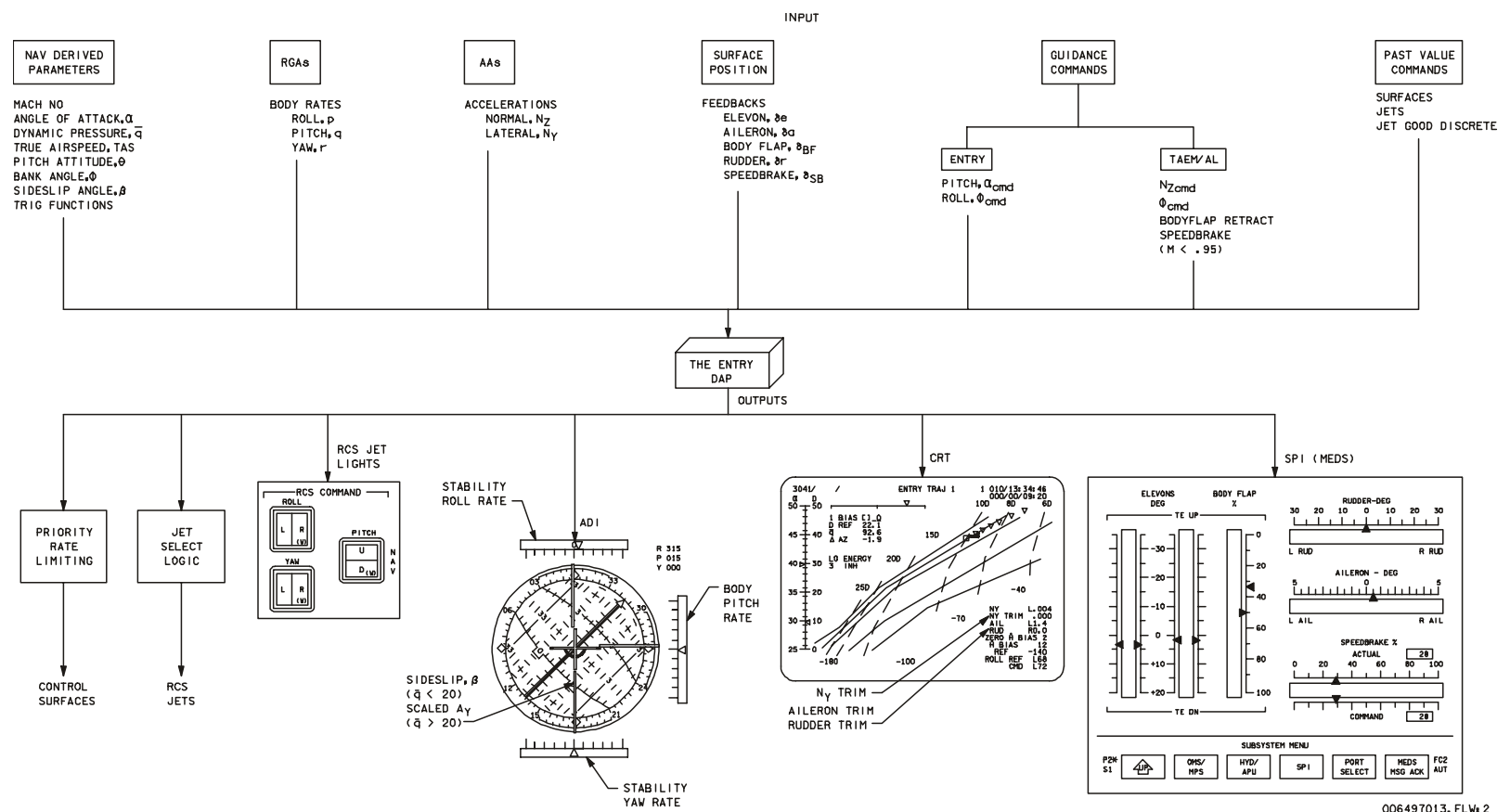
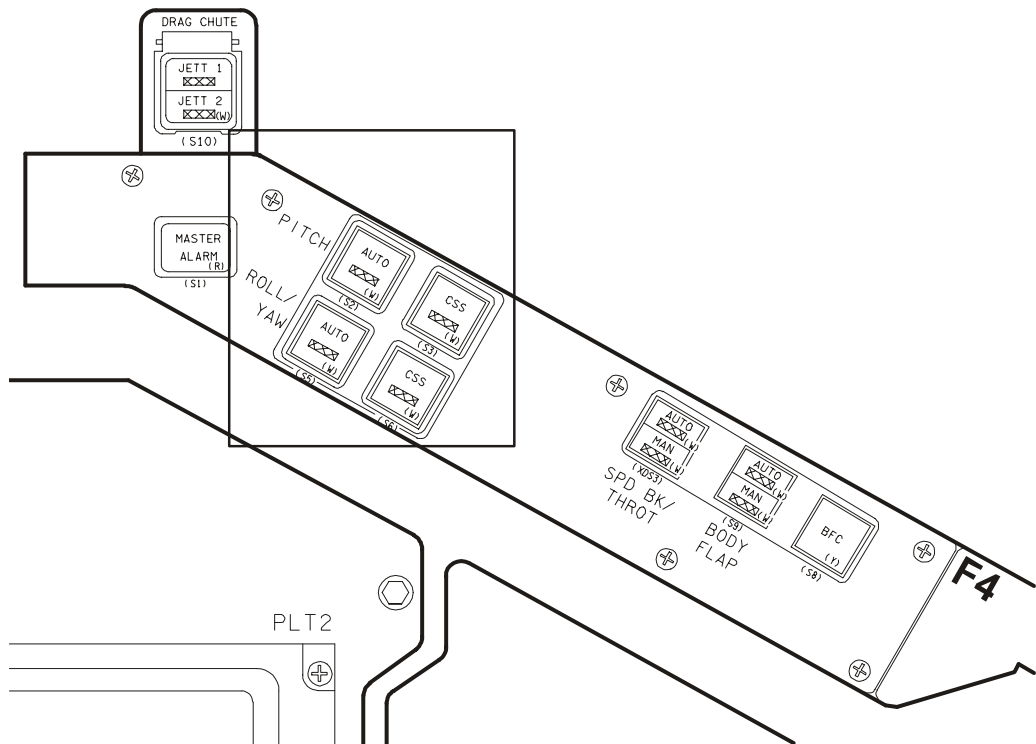


Figure 1-2. Entry DAP

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Typically, on a nominal EOM entry and landing, the orbiter is left in AUTO, allowing the shuttle flight software to guide the orbiter, on automatic pilot, through the entry down to about 50,000 feet altitude and subsonic speeds. The crew has the capability to manually fly the orbiter through all phases of the entry and landing. Throughout this workbook, reference will be made to the manual, or CSS, flight control modes and cockpit switches. Following is a brief overview of the manual flight controls available to the crew on the flight deck.

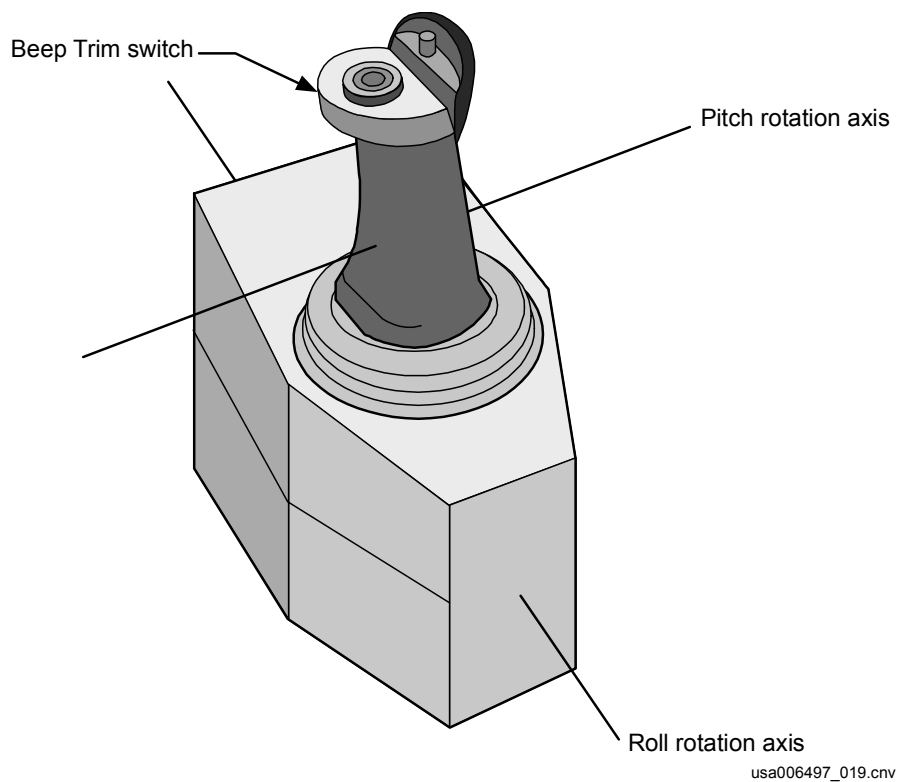
To “take CSS,” the crew must either depress the CSS pushbutton for pitch and roll/yaw, or may use the RHC to “hot stick downmode” from AUTO to CSS. The takeover pushbuttons are on Panels F2 and F4 in front of the commander and pilot, respectively (see Figure 1-3). Additionally, the appropriate flight controller power switch, on Panel F6 or F8, must be on, and the Display Driver Unit (DDU) circuit breakers, on Panels O14, O15, and O16, must be closed/in to provide power to the RHC.



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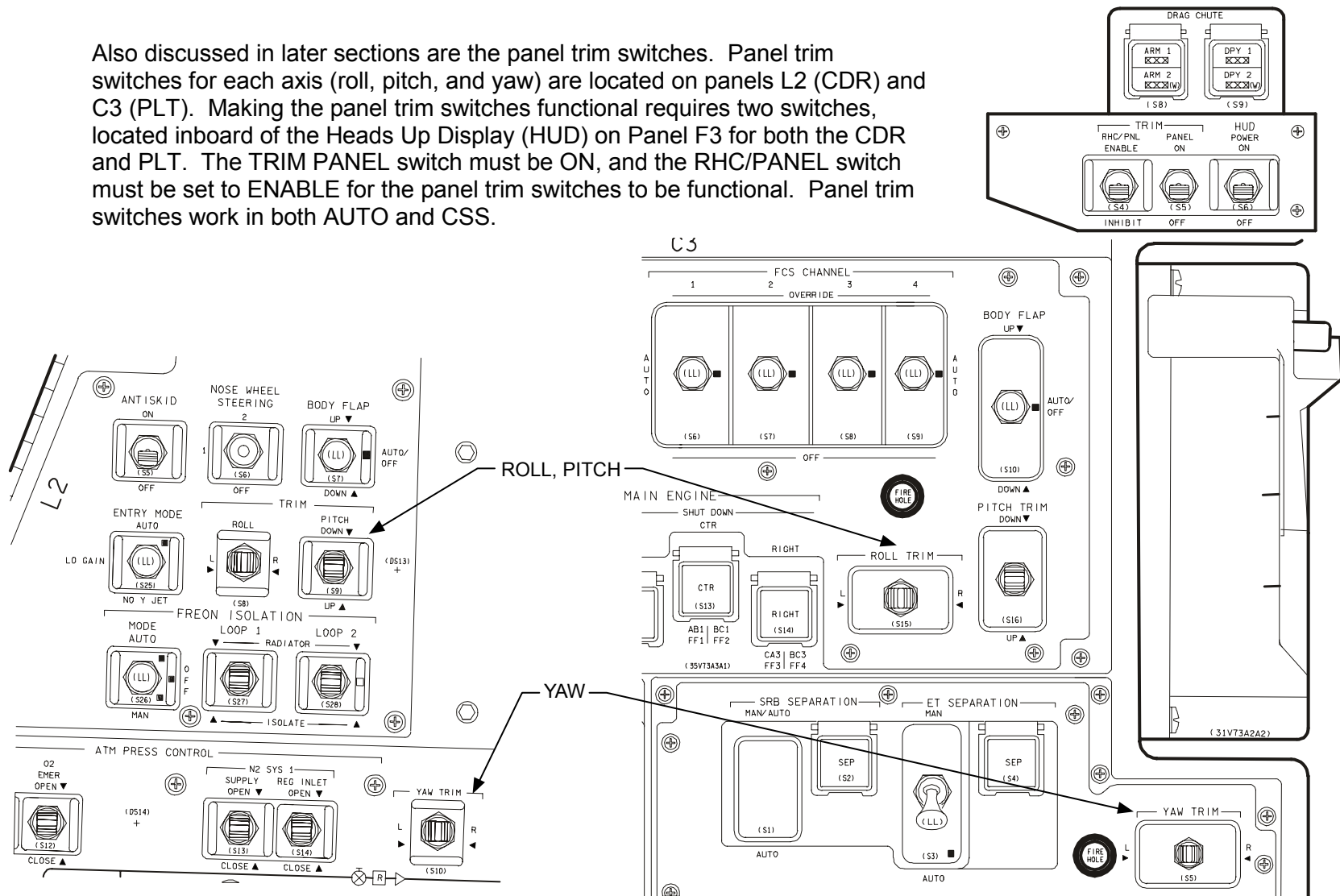
**Figure 1-3. PLT Panel F4 AUTO/CSS pushbuttons**

The RHC is the primary flight controller for a manual entry. It is only functional in the roll and pitch axes during entry. On the top of the RHC, to the left of the BFS Engage pushbutton, is the RHC trim switch, also known as the “beep trim” switch (Figure 1-4). Beep trim is only functional when in CSS for the appropriate axis, roll, or pitch. The RHC/PANEL trim switch must be in ENABLE (Panel F3) for the beep trim to be functional. The software that controls the beep trim switch changes after landing; details are not covered here.



**Figure 1-4. Rotational hand controller**

Also discussed in later sections are the panel trim switches. Panel trim switches for each axis (roll, pitch, and yaw) are located on panels L2 (CDR) and C3 (PLT). Making the panel trim switches functional requires two switches, located inboard of the Heads Up Display (HUD) on Panel F3 for both the CDR and PLT. The TRIM PANEL switch must be ON, and the RHC/PANEL switch must be set to ENABLE for the panel trim switches to be functional. Panel trim switches work in both AUTO and CSS.



006497032, PNL 8 1

Figure 1-5. Panel trim switches



The rudder pedals, which are connected to the Rudder Pedal Transducer Assemblies (RPTAs) are active in roll/yaw CSS below Mach 5. Typically the rudder pedals are not used until landing rollout on the runway. At that point, the rudder pedals are used for nose wheel steering and brakes. The function of the RPTA is discussed further in the yaw axis section of the workbook.

The BODY FLAP and SPBK also have manual controls available. These will be discussed in later sections of the workbook specific to the BODY FLAP and SPBK functions.

Table 1-1 to Table 1-4 are compilations of important Entry DAP numbers. These sets of numbers are the maneuver rates, aerosurface deflection position and rate limits, and the RHC deflection limits, including AUTO to CSS downmode limits.

**Table 1-1. Entry DAP maneuver rates and manual trim bias**

	Rates (deg/sec)		Trim bias (deg/sec)		
	Early entry (AUTO/CSS)	Ramp increase to:	RHC beep trim	Panel trim	
ROLL, $\Phi$	$p$	3.0 Auto (M>23.5) 5.0 Auto (M<23.5) 6.0 CSS	20 Auto (M1.5 – 0.6) 27 CSS	2.5	0.5
PITCH, $\Theta$	$q$	0.5 Auto 2.88 CSS	9.2 Auto & CSS (M2 – 1.2)	1.5	2.0
Ny command (g)					
YAW, $\Psi$	$r$	0.9 lateral g	N/A	0.1 g	

**Table 1-2. Entry DAP aerosurface deflection limits**

Aerosurface		Engineering units		Display units
		Hardware limit	Software limit	
Elevon	Up	-36.5°	-33°	33° Up 18° Down
	Down	+21.5°	+18°	
Aileron	Left		-10°	5° Left 5° Right
	Right		+10°	
Rudder	Left	+27.1°	+24.1° <sup>1</sup>	27° Left 27° Right
	Right	-27.1°	-24.1°	
Speedbrake	Close	-9.9°	-9.9° <sup>2</sup>	0 % 100 %
	Open	+98.6°	+98.6°	
Body Flap	Up	-15.7°	-11.7°	0 %
	Trail	0°	0°	34 %
	Down	+26.5°	+22.5°	100 %

<sup>1</sup> In-flight rudder limit. Rollout limit is  $\pm 26.6^\circ$ .

<sup>2</sup> Once commanded open, the SPBK software close command limit is 15° (15%).

Trim Limits – Aileron: 3.0° (Baseline); 5.0° (Wraparound)

Rudder: 6.0°

**Table 1-3. Entry DAP aerosurface drive rate – Priority Rate Limiting**

Aerosurface	Drive rate (deg/sec)		
	3 APUs	2 APUs	1 APU
Elevon	20	20	13.9
Rudder	14 (5.43 sumlim)	12 (5.43 sumlim)	7 (1.9 sumlim)
Speedbrake	Close	10.86	6.06 (3.8 sumlim)
			Open
Body Flap <sup>1</sup>	2.4	1.6	0.8

Sumlim – The rudder and SPBK are the same surfaces.

When the combined commands open the panels to greater than 52.9°, the drive rates are decreased in PRL.

<sup>1</sup> Body Flap drive rates are expected minimums, per test data.

APU – Auxiliary Power Unit

**Table 1-4. Entry DAP CSS downmode limits**

Axis	Deadband	Soft stop	Hard stop	CSS downmode
Roll	1.25°	±19 - 20°	±24.3°	6.0
Pitch	1.15°	±19 - 20°	±24.3°	6.0 21.7 LREL
Yaw	0.65°	±9.5 - 10.5°	±14.3°	6.0

LREL – LOAD\_RELIEF = ON

RHC Yaw axis inop in MM304/305, 602/603

“DAP DNMODE RHC” caution and warning message in PASS

when:

OPS 1, 2, 3, or 6 (except MM102, 103, 601)

DAP is AUTO

Mach ≥ 1

RHC moved beyond the downmode threshold

## QUESTIONS

1. Which two control systems does the entry DAP command?
2. What are the two ways entry DAP is provided with command rates?
3. Which input data are necessary for determining control requirements?

## **2.0 PITCH CHANNEL**

### **2.1 OBJECTIVES**

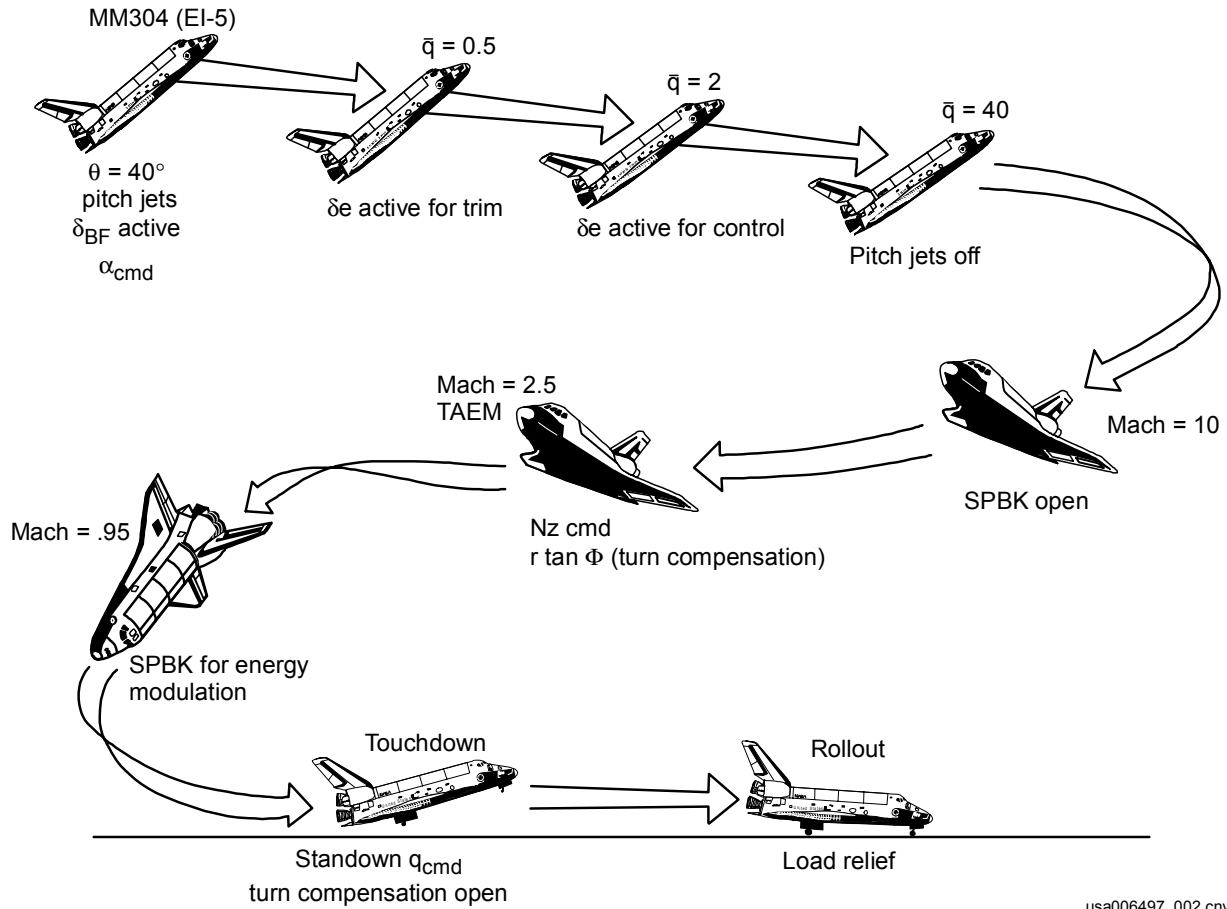
At the end of this section, the student will be able to list the three separate aerodynamic control surfaces that control the pitch attitude of the shuttle. The student will also be able to do the following:

- a. State when the pitch jets are deactivated
- b. State when the elevators are active for control
- c. Describe turn compensation
- d. Describe load relief bias
- e. Describe the primary purpose for the BF
- f. Describe how the crew can manually position the BF
- g. List the two purposes of the SPBK
- h. Describe the use of the SPBK in the 3000 feet of descent before touchdown

### **2.2 INTRODUCTION**

Figure 2-1 is an overview of the major entry DAP events in the pitch channel from MM304 at Entry Interface (EI) minus (-) 5 minutes through touchdown and rollout. These events are described in greater detail in subsequent sections.

Three separate aerodynamic control surfaces, as well as the pitch RCS jets, are active in controlling the pitch attitude of the vehicle. The surfaces are the elevons, the BF, and the SPBK.



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Figure 2-1. The pitch channel

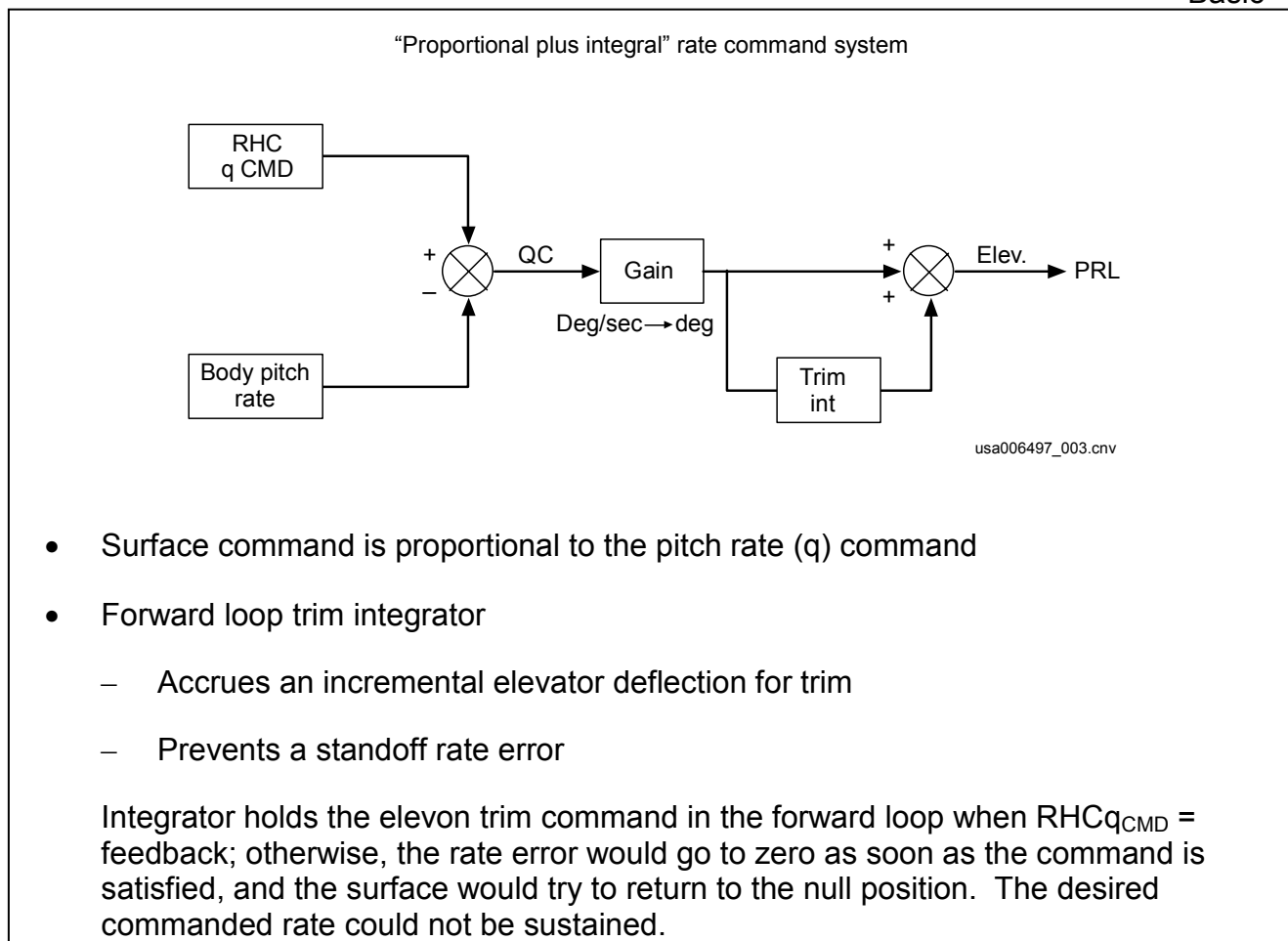
## 2.3 ELEVATORS

Pitch axis control is provided by the elevators (aerodynamically) and the pitch RCS jets (low  $\bar{q}$ ). The control system is a proportional-plus-integral rate command system, meaning that the elevator surface command is proportional (through the gain shown) to the Auto or RHC commanded rate (Figure 2-2). This elevator command is summed with the output of an elevator trim integrator in the forward loop, resulting in an elevator command to the priority rate limiting software.

The forward loop trim integrator accrues an incremental elevator deflection for pitch trim and prevents a standoff rate error. In other words, as the commanded rate is being satisfied (command equals feedback), the rate error would go to zero at the summation point, and without the trim integrator to hold the elevator at the last commanded position, the desired commanded rate could not be sustained.

Figures 2-2 through 2-6 show buildup of the Flight Control System (FCS) pitch channel of the entry DAP. These figures are slightly more detailed, but are still in a simplified form for ease of understanding and logical step-by-step additions of the various functions of the pitch channel. A complete schematic of the pitch channel, as well as those of the SPBK and the BF, is contained in the Functional Subsystem Software Requirements document STS-83-0007, Entry Flight Control.

The reader should note that the elevons are the actual aerosurfaces on the vehicle. Elevators refer to the use of the elevons symmetrically for pitch control; ailerons refer to the use of the elevons asymmetrically for roll control.

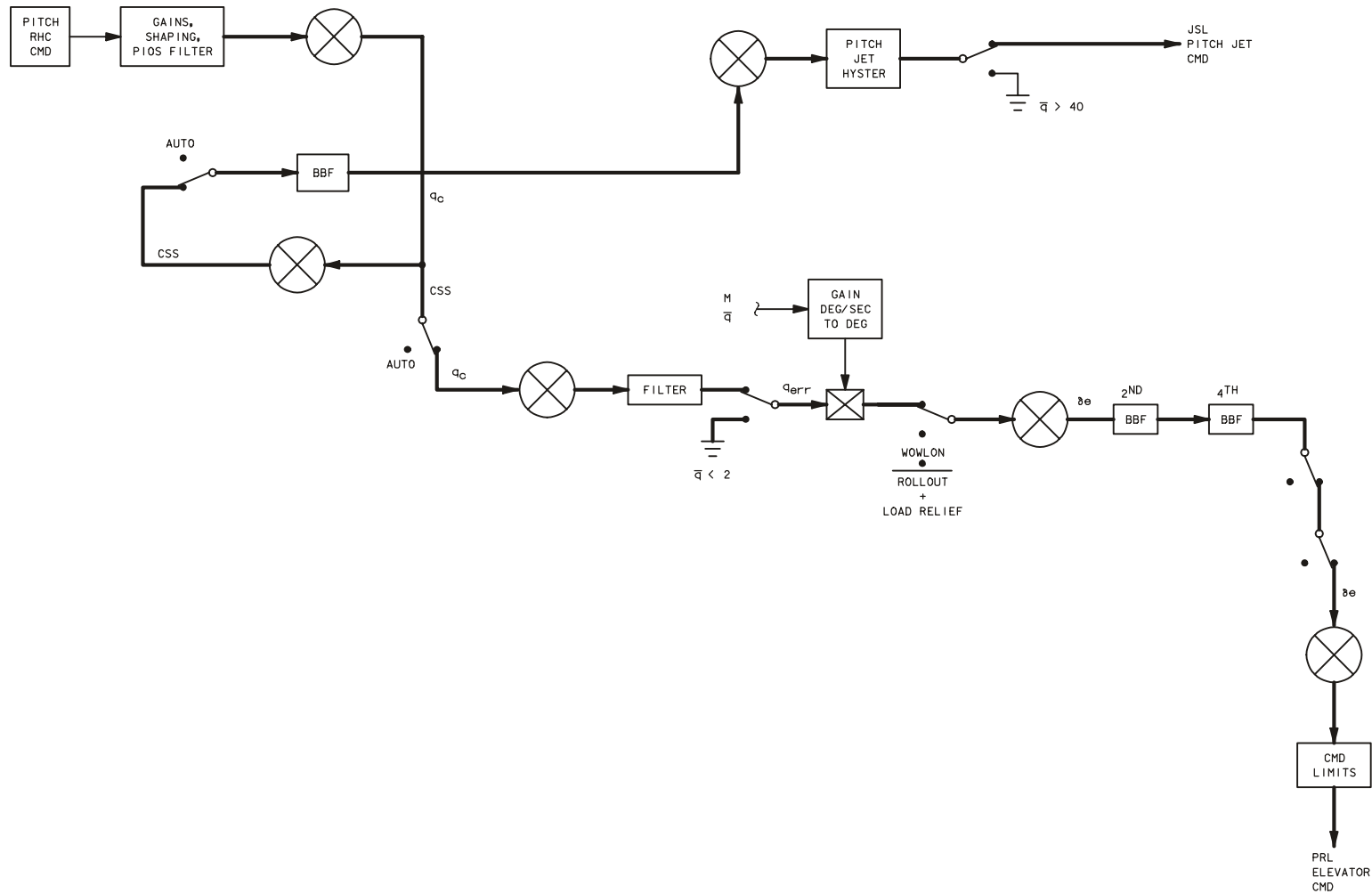


**Figure 2-2. Pitch axis**

Figure 2-3 shows the CSS command path in the pitch channel. The CSS commands are input through the RHC. From there, the input, which is commanded pitch rate ( $q_{cmd}$ ), takes two paths. Path 1 goes through various filters into the pitch RCS jet hysteresis logic, which determines whether to fire an RCS jet. Assuming that a jet command is issued, it goes out to the Jet Select Logic (JSL) to fire the pitch jets. A switch is opened when the  $\bar{q}$  becomes greater than 40 psf, negating further use of the pitch jets during entry.

Path 2 of the commanded pitch rate goes through filters and is multiplied by a gain that converts a pitch rate error into an elevator command. This command is compared to surface position limits and sent to Priority Rate Limiting (PRL), where the surface commands are issued. The elevons become active when  $\bar{q}$  is greater than 2 psf.





006497021, SCH 1

Figure 2-3. FCS pitch channel buildup – CSS commands

Figure 2-4 shows a turn compensation term active at the beginning of the TAEM phase and is used until touchdown. Turn compensation, which is calculated using measured parameters, is the amount of pitch rate needed to keep the nose of the vehicle up during a turn for a nearly constant flight path angle.

Figure 2-4 also shows the addition of rate feedback and trim loops. The body pitch rate,  $q$ , is the feedback value with which the RHC or automatic commanded pitch rate,  $q_{cmd}$ , is differenced to give pitch rate error,  $q_{err}$ . The pitch rate error, while going on to command the elevators and the pitch jets, also goes into the pitch trim integrator loop for low  $\bar{q}$  trim ( $\bar{q} < 40$  psf). The pitch trim integrator becomes active at a  $\bar{q}$  of 0.5 psf, when the elevators respond to pitch jet firings. At a  $\bar{q}$  of 2 psf, the elevators become fully active for control. The trim integrator no longer receives pitch jet firing commands after  $\bar{q}$  passes 8.0 psf and is switched out in favor of elevator position feedback trim at  $\bar{q}$  equal to 40 psf.

An increment to account for the pitching moment of the SPBK is added to the elevator feedback position and is also shown in Figure 2-4.



Figure 2-5 shows the addition of the pitch panel trim switch, the RHC rate trim switch, the normal acceleration ( $N_z$ ) command, and the PTI modifications.

The pitch panel trim switch feeds directly into the elevator trim loops. When this switch is activated, the elevators are driven to a new position, generating a pitch rate. The pitch rate causes an error in either angle of attack ( $\alpha$ ) or  $N_z$  to develop. When the trim switch is released, thereby removing the pitch command, in Automatic Pitch (AUTO P) the control system will automatically begin to remove any  $\alpha$  or  $N_z$  error, and return the vehicle to its original attitude. The same pitch panel trim input while the vehicle is in pitch Control Stick Steering mode (CSS P) creates a slightly different result. The same  $\alpha$  or  $N_z$  error will develop, but when the input is ended, the DAP will only damp out its rate, leaving the vehicle at some new pitch attitude. The body flap will likely respond to this new attitude as it works to keep the elevons on or near a position schedule. Currently, there is no operational use of the pitch panel trim switch.

Similarly, the RHC rate trim switch ("Beep Trim"), functional only in CSS P, biases the rate signal coming from the RHC with a constant rate input. The pitch bias limit is  $\pm 1.5$  deg/sec. Once the rate bias is commanded, it will remain until it is removed by either "beeping" the switch the opposite direction or by going from CSS P to the automatic mode, AUTO P, which reinitializes the integrator and immediately removes any rate bias that has been commanded. Operationally, pitch beep trim is used to derotate the vehicle during landing rollout after main gear touchdown. The roll beep trim switch is discussed in a later chapter.

The PTI modification to the pitch channel is also identified in Figure 2-5. There is one PTI in the jet command loop and one in the elevator command loop. As can be seen, these go directly to the jets or the elevators, bypassing any gains or filters. This is done to obtain the correct control input for the investigation of the aerodynamics or response characteristics of the shuttle. PTIs are discussed in more detail in Section 11.



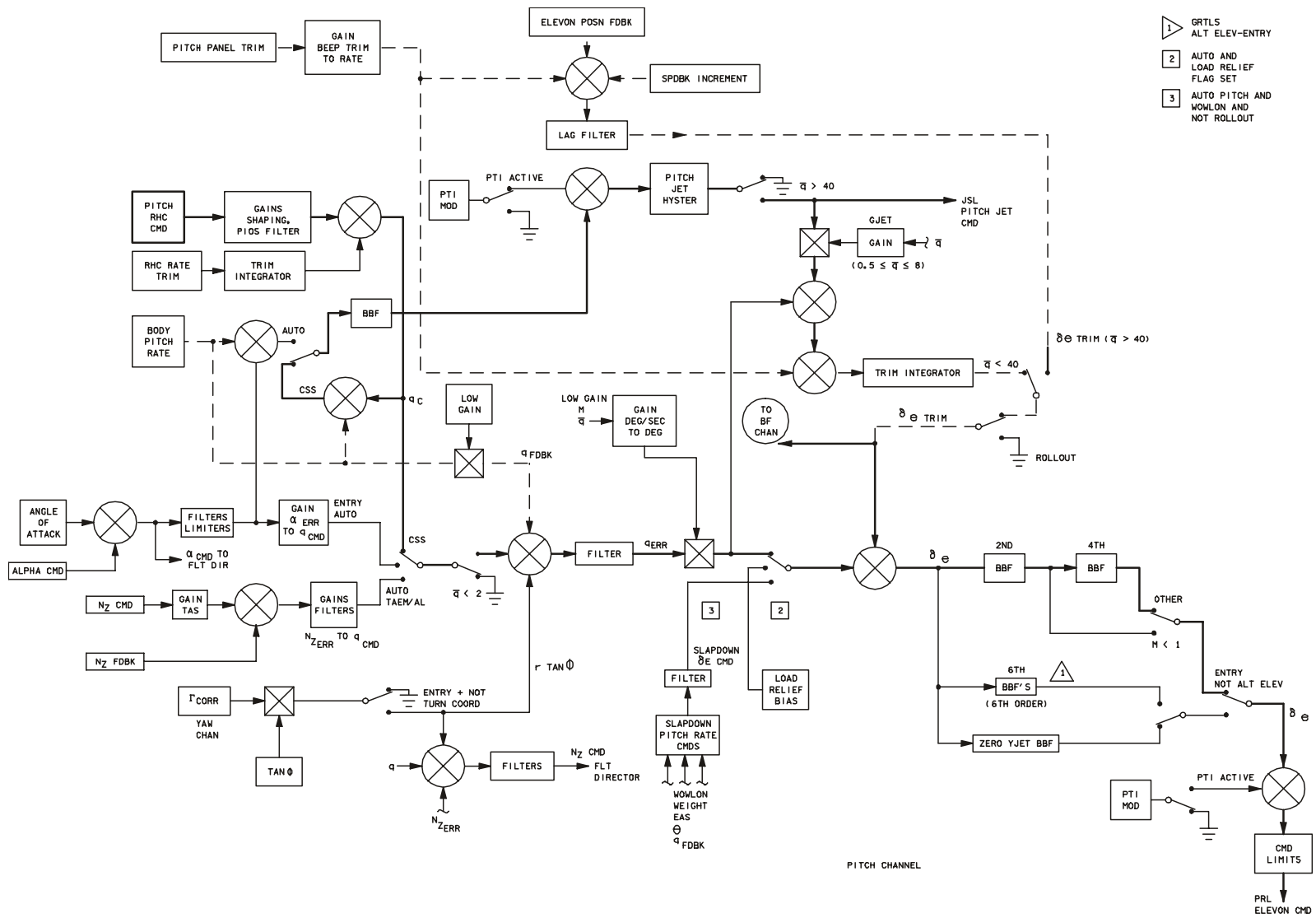
In Figure 2-6, the automatic commands, which concludes the pitch channel schematics, adds the automatic control loop, the low gain option, the GRTLS or alternate entry gain changes, the load relief bias, and the automatic slapdown commands, are divided into two distinct parts. For early entry, the auto commands are based on  $\alpha$ . The  $\alpha$  command comes from guidance, is differenced with the angle of attack feedback, and (after going through filters and gains) goes to the pitch jet loop and the elevator loop. The unfiltered, ungained difference is also sent to the pitch error needle of the ADI.

The auto pitch system changes from  $\alpha$  command to  $N_z$  command at the TAEM interface. Here, the  $N_z$  command is differenced with the feedback to generate the proper pitch command. Also, when the pitch control changes from  $\alpha_{cmd}$  to  $N_{zcmd}$ , the  $N_{zerr}$  is taken from the pitch channel, conditioned, and sent to the ADI pitch error needle, as shown in Figure 2-6.

The two methods of pitch control are used, depending on the methods of trajectory control in early entry as compared to the late entry phase. In early entry, the longitudinal axis (pitch) is not the primary method of controlling the energy state; this is done by the bank angle, while the high angle of attack being flown is providing heating protection. It is easy, therefore, to fly a known alpha profile and base the pitch control on alpha command.

In the TAEM phase, the bank angle is used for controlling direction and is basically a function of the azimuth to the Heading Alignment Cone (HAC). The longitudinal axis is now controlling the energy state; thus, the guidance is controlling the energy state with altitude, altitude rate,  $\bar{q}$ , and the normal acceleration. If the vehicle is near nominal energy, the  $N_z$  command is primarily a function of getting to the proper altitude versus range profile. This is limited by high and low energy protection. The command for the altitude correction is then compared to the  $\bar{q}$  boundaries to ensure that it will keep  $\bar{q}$  within limits. This  $N_z$  command then goes to the FCS.

The low gain option, a function of the entry mode switch, provides a gain reduction in all three axes should the need arise. In the low gain position, the gains to the control surfaces are halved to protect against a high frequency oscillation on the surfaces.



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Figure 2-6. FCS pitch channel buildup – auto entry and TAEM guidance CMDs

Another path to be taken in the event of a GRTLS abort or selection of the alternate (FIXED) elevon schedule is also shown. This GRTLS schedule is automatically selected during a launch abort (MM 602).

The AUTO elevon schedule and nominal body-bending filter are automatically selected during a nominal entry. The FIXED elevon schedule can be selected on SPEC 51, OVERRIDE by the crew. Elevon schedules are discussed further in the Body Flap section of this workbook.

The nominal and alternate (or payload) body-bending filters can be similarly selected by the crew. The payload filters would be selected for heavier than normal payloads, or when the payload mounting may exhibit structural damping characteristics for which the nominal body-bending filters were not designed.

At main gear touchdown, pitch rate commands for lowering the nosewheel are generated as a function of vehicle weight and are sent to the ADI flight director. The commands are converted into elevator commands when the vehicle is being flown in pitch AUTO. This is the slapdown pitch rate command.

The last item shown on the pitch channel is the load relief bias that assists in offloading the main landing gear during rollout. It is designed so that in AUTO the elevators are driven down, which reduces the load on the main tires and gear. If flown in CSS P, the DAP will mode to AUTO P when the load relief flag is set. The elevator position will be based on a schedule that is a function of ground speed. The position command is  $10^\circ$  down for all ground speeds. Should the crew need to intervene in pitch, pitch control can be taken by moving the RHC  $21.7^\circ$  out of detent (nearly to the hard stop) or by moding to CSS with the pushbutton. This logic also works in the BFS.

## **2.4 BODY FLAP**

The BF, as previously stated, is a pitch trim device that is used to keep the elevons on or near a predetermined schedule. Whether the elevons are kept on, or just near, the predetermined schedule depends on whether the crew has the AUTO or FIXED elevon schedule selected and, for the AUTO schedule, the position of the BF.

The AUTO elevon schedule and BF combination is designed to keep the elevons positioned where they can be the most effective without exposing the BF or elevons to excessive heating or high hinge moments. Figure 2-7 shows that the elevon trim command is fed into the BF channel, where it is differenced with the BF position and the elevon schedule. As the BF moves up, the elevons move down. As the BF moves down, it drives the elevons up. The BF moves so as to drive the elevon trim command toward the elevon schedule.

The difference between BF position, elevon position, and elevon schedule is compared to a deadband. If the error is greater than  $1^\circ$ , the signal is differenced with the BF position to determine if the BF is within  $1^\circ$  of the required position. If not, the BF is driven up or down until the elevon trim loop is satisfied. As the BF moves toward the full up or down position, a Mach and position-dependent bias is added to the elevon trim to



bias the elevon position. This causes the elevon position to shift up to 6° up or down, preventing the BF from saturating for extreme off-nominal c.g. This ability to handle the full c.g. range without BF saturation, making AUTO elevon selection independent of Xcg, is the primary advantage of the AUTO schedule.

The FIXED elevon schedule/BF is similar to the AUTO elevon/BF, except that the BF position is not added to the elevon trim and elevon schedule. The BF moves as described above to keep the elevons on schedule, even if the BF must drive full up or down, and the elevon position is not biased to prevent BF saturation. This is the primary disadvantage of the FIXED schedule; it can handle only approximately one-third of the total c.g. range without BF saturation. This could result in high hinge moments or thermal problems for the BF; therefore, the FIXED elevon schedule is based on a generic forward, mid, or aft Xcg location on a flight-specific basis. For most flights, a generic aft c.g. FIXED elevon schedule is I-loaded, which places the elevons in their furthest down position. We would see this selection during no yaw jet operations.

An example of an elevon schedule, along with the BF schematic, is shown in Figure 2-7. The elevon schedule is a function of Mach. The AUTO elevon schedule is automatically selected upon transition to Operations Sequence (OPS) 3, whether the transition is from OPS 1 or OPS 2. The FIXED schedule must be manually selected. AUTO/FIXED elevon selection is made on Guidance, Navigation, and Control (GNC) SPEC 51 OVERRIDE in both PASS and BFS. A third elevon schedule, the GRTLS schedule, is automatically selected upon Return to Launch Site (RTLS) abort select. No crew input is required or allowed. The GRTLS elevon schedule is configured based on expected GRTLS c.g.

The crew can also operate the BF manually. The BF pushbutton indicator (pbi) on Panel F2 or F4 toggles between AUTO and manual (MAN) when pushed (Figure 2-8). MAN enables the BF switch on Panel L2 or C3 (spring loaded to off). This allows the crew the option of taking control of the BF and manually positioning the BF where desired. If the BF is manually moved up, the elevons are commanded down to maintain control and trim. The opposite is also true, moving the BF down drives the elevons up. Caution must be used when manually driving the BF. If the BF is moved down too far, the elevons can be driven up to the point that they lose control effectiveness. This could lead to a loss of vehicle directional control. BF rate during manual operations is faster than the rate during AUTO operations. Manual BF is used for some off-nominal aerodynamics cases in which the BF is raised to lower the elevons, increasing elevon effectiveness.

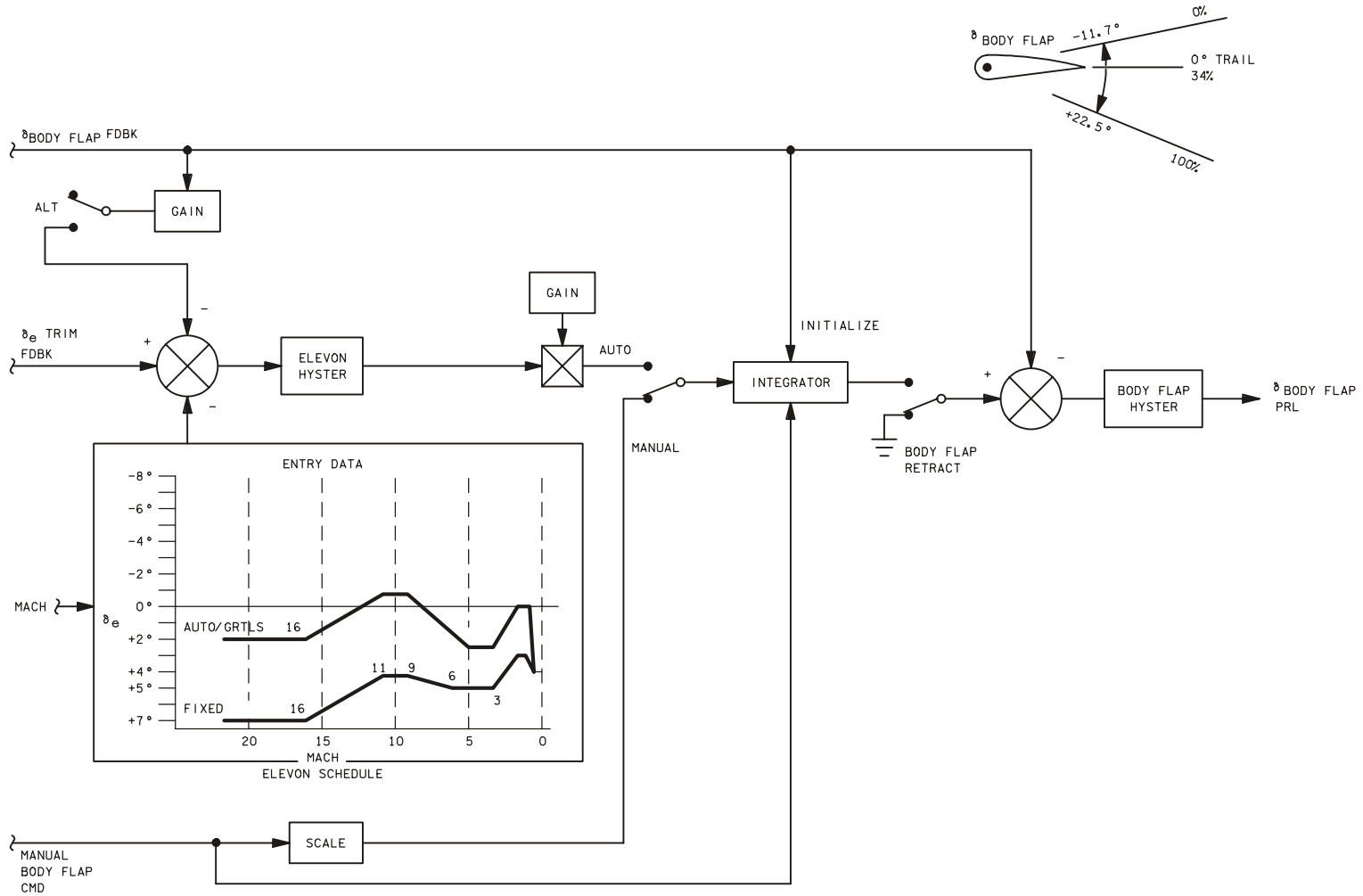
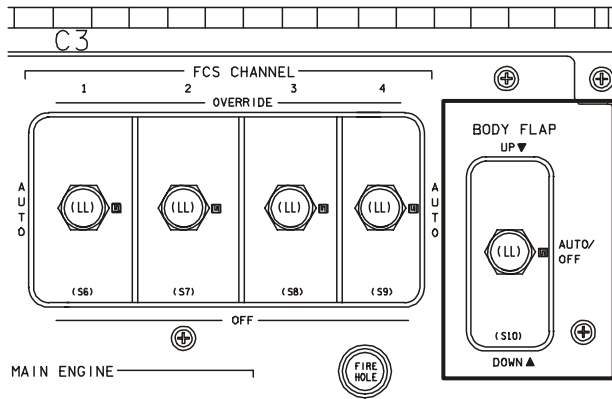
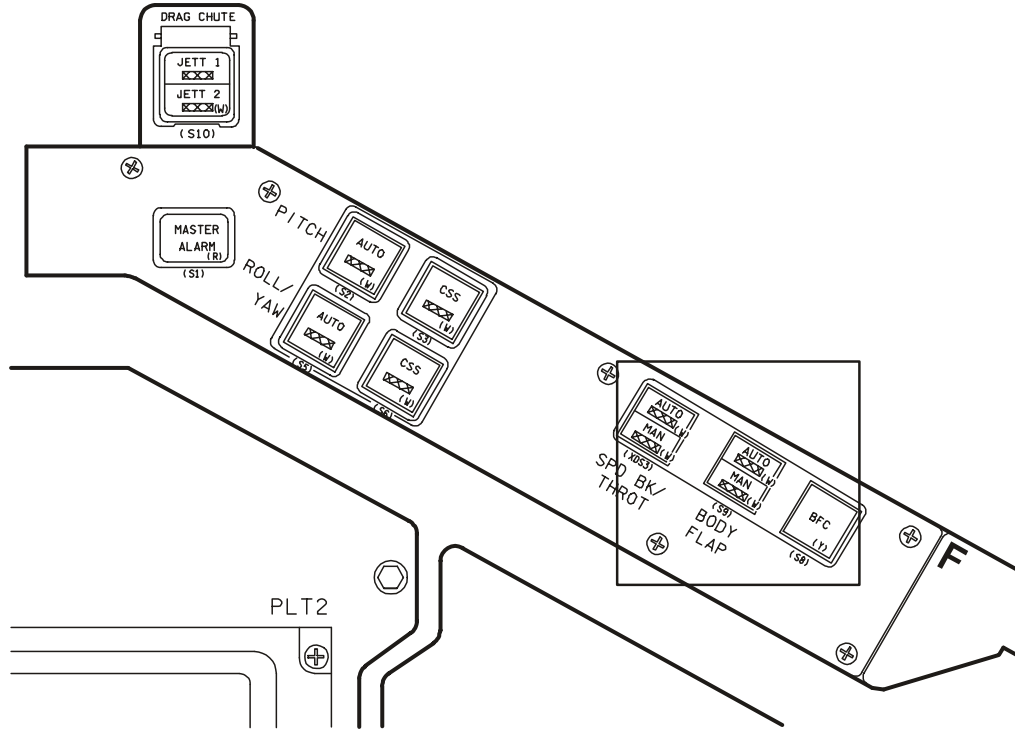


Figure 2-7. The body flap channel

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Figure 2-8. Manual body flap controls (PLT Panels shown)

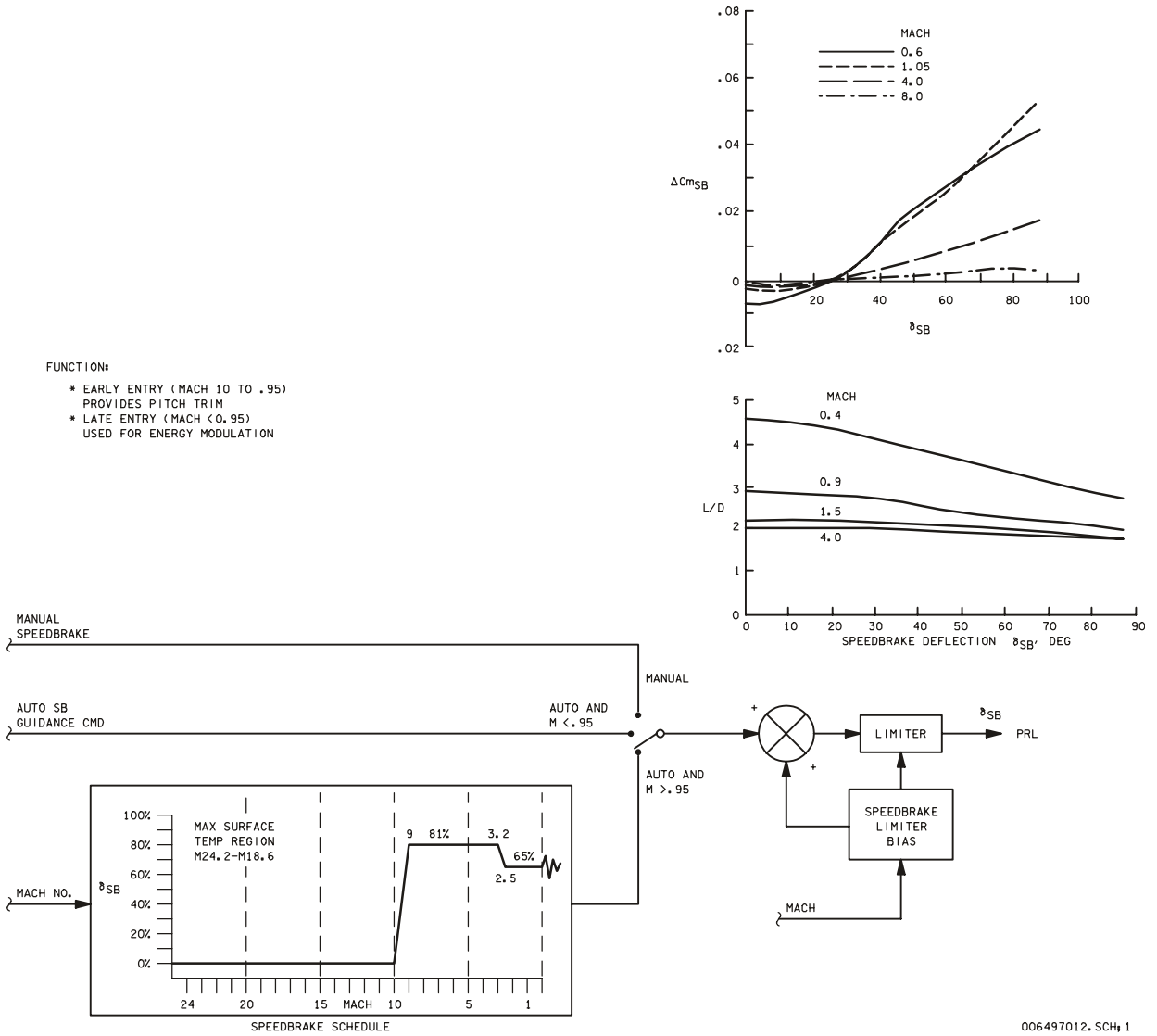
## 2.5 SPEEDBRAKE

Opening at Mach 10, the SPBK is used to aid in trimming the vehicle in pitch down to Mach 0.95 and is also used to modulate energy below Mach 0.95. Some of the aerodynamic characteristics of the SPBK are shown in Figure 2-9. The figure shows the pitching moment contribution ( $\Delta C_{m_{SB}}$ ) for various SPBK angles and Mach numbers and the Lift-to-Drag (L/D) contribution for the same parameters. These data show that while there is a change in pitching moment with SPBK angle, starting with Mach numbers as high as 8.0, there is little change in L/D until the Mach number is subsonic. This positive, nose up, pitching moment results in the elevons being driven down to retrim the orbiter, making the elevons more effective control devices.

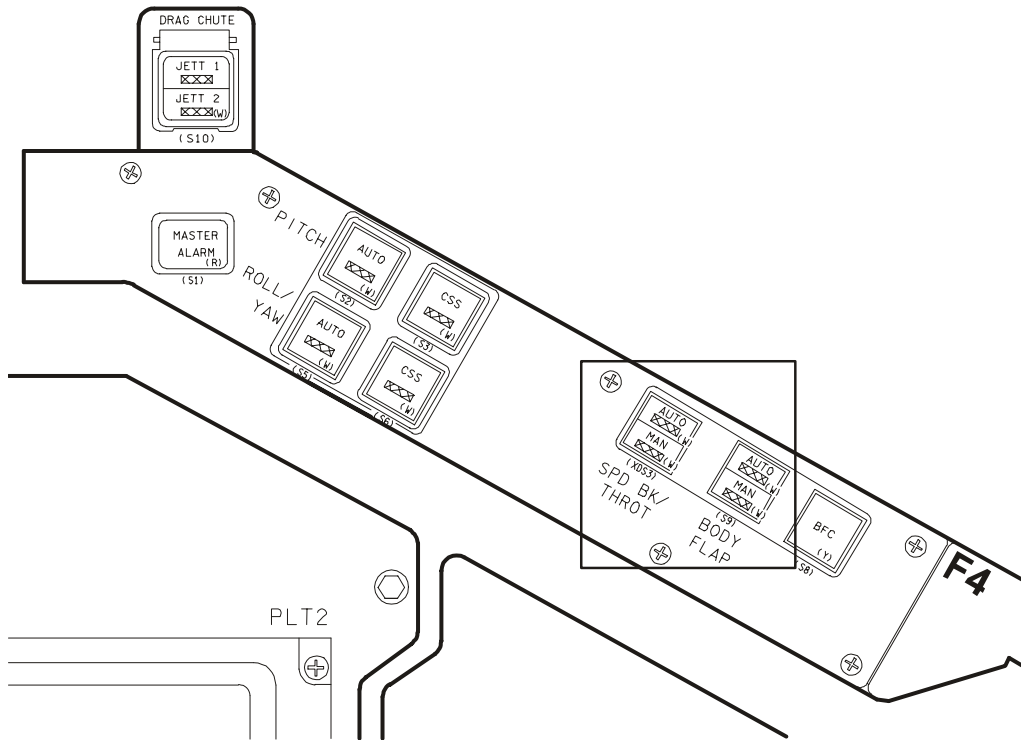
During ascent and the first part of entry, the SPBK closed command is  $-9.9^\circ$  to ensure a tightly closed condition, preventing any heat damage. The SPBK has a programmed schedule for entry. The schedule keeps the SPBK closed until Mach 10, at which point it is commanded to an open position (81 percent). At Mach 3.2, the SPBK is closed to 65 percent to allow the rudder to be more effective. The schedule holds this position until the Mach number reaches 0.95. The SPBK is then used by guidance to modulate energy. An example of this schedule is shown in Figure 2-9.

A simple schematic of the SPBK channel is shown in Figure 2-9. In the automatic mode, the SPBK command is driven by the SPBK schedule at Mach numbers above 0.95 and by guidance below 0.95. From Mach = 0.95 until 14,000 feet Above Ground Level (AGL), guidance uses the SPBK to control total energy: airspeed and altitude. From 14,000 feet AGL down to 9000 feet AGL, the H-Blend altitude, SPBK control transitions from total energy control to pure airspeed control. Below 9000 feet AGL if above the reference airspeed (300 knots), the SPBK extends; if below the reference airspeed, the SPBK retracts. In the 3000 feet before touchdown, guidance will adjust the SPBK twice, once at 3000 feet AGL and again at 500 feet AGL to ensure that the shuttle reaches the desired touchdown point at the desired airspeed. At 3000 feet AGL, guidance uses velocity error (from a reference velocity), vehicle weight, wind, density altitude, runway option (nominal, short field, or Emergency Landing Site (ELS)), and aimpoint selection (nominal versus close-in) to set the SPBK retract angle. At 500 feet AGL, guidance uses wind and density altitude for SPBK adjustment. These commands are summed with a limit bias to prevent contact with the hard stops and go through a SPBK limit logic out to the PRL.

Manual operation of the SPBK is available to the CDR or PLT by depressing the takeover pushbutton on the Speedbrake Thrust Controller (SBTC), with the command coming from the crew via the SBTC. See Figures 2-10 and 2-11. Moving the SBTC forward closes the SPBK, and moving the SBTC aft opens the SPBK. A scale, attached to the console adjacent to the SBTC, aids the crew in setting the SPBK position. Note that only one SBTC (CDR or PLT) can control the SPBK at a time. The MAN light in the SPD BK/THROT pbi on Panel F2 or F4 indicates which SBTC is in control. Automatic SPBK control is regained by depressing the SPD BK/THROT pbi on Panel F2 or F4.

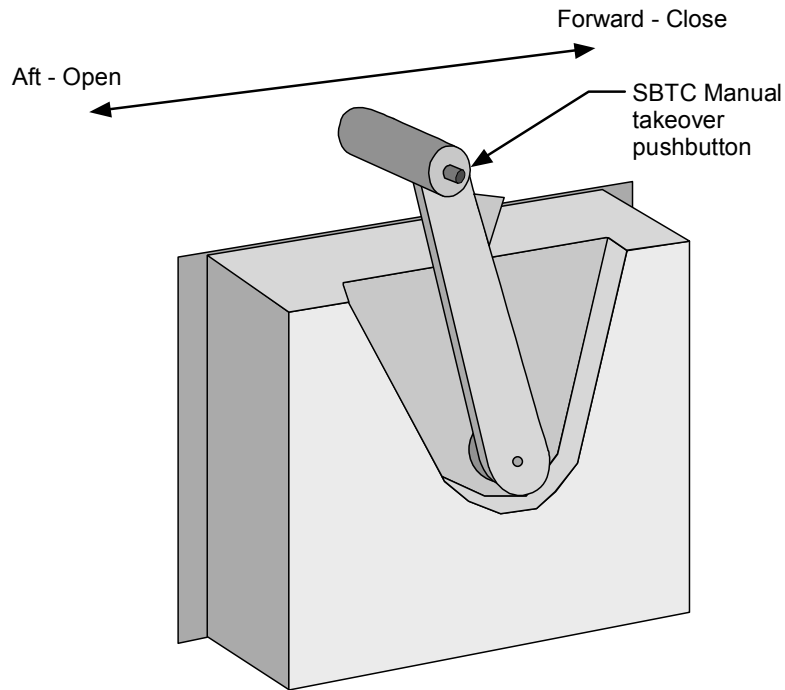


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Figure 2-10. Manual SPBK controls



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Figure 2-11. SPBK thrust controller

## QUESTIONS

1. Which three separate aerodynamic control surfaces control the pitch attitude of the shuttle?
2. When are pitch jets deactivated?
3. When are elevators active for control?
4. Describe turn compensation.
5. Describe load relief bias.
6. What is the purpose of the BF?
7. What is the difference between the AUTO and FIXED elevon schedule?
8. How can the crew manually position the BF?
9. What are the two purposes of the SPBK?
10. How can the crew manually position the SPBK?

### 3.0 LATERAL-DIRECTIONAL CONTROL

#### 3.1 OBJECTIVES

At the end of this section, the student will be able to do the following:

- a. Describe the stability axis system
- b. Describe the process in which lateral-directional control is maintained by first generating, then controlling sideslip
- c. Describe the differences between the early and late regions of lateral-directional control
- d. Describe the significance of Gain for Ailerons in Roll Channel (GALR)
- e. Describe the condition that must be satisfied for the shuttle to be trimmed
- f. List the lateral-directional control effectors for trim
- g. State when the rudder becomes active for trim

#### 3.2 INTRODUCTION

The roll and yaw channels need to be introduced together because the lateral-directional control of the orbiter is coupled (as in any aircraft) so that motion in one axis has an effect in the other axis, and with the shuttle it can at times be profound. After firmly establishing this relationship, the schematic of each axis is discussed individually.

At Mach numbers greater than 5.0, the high angle of attack being flown blanks the vertical tail to such an extent that the rudder is virtually useless. This makes the use of yaw jets and ailerons necessary to keep sideslip angle within controllable limits at higher Mach numbers. The use of yaw jets (yaw axis) and ailerons (roll axis) provides lateral-directional control, with the rudder coming into play much later.

To assist understanding the roll/yaw control interaction, the stability axis system is introduced here. The stability axis system is shown in Figure 3-1, along with its relationship to the body axis system. The stability axes differ from the body axes by the displacement of the X- and Z-axes following a rotation about the Y-axis through the angle of attack,  $\alpha$ . By definition, the sideslip angle,  $\beta$ , is the result of a rotation about the stability yaw axis. The sideslip angle is then the angle between the stability X-axis and the projection on the body X-Z plane of the velocity vector of the orbiter.

The key to early entry lateral-directional control is the orbiter's natural instability in the region. Yaw due to jet firings and/or adverse yaw (i.e., yaw due to aileron deflection) causes a yaw rate to develop. Being unstable, if left unchecked, sideslip due to yaw would increase, couple into roll, and send the orbiter out of control. The roll and yaw channels of the entry DAP use this adverse yaw characteristic and roll due to sideslip



in a controlled fashion to accomplish bank maneuvers. At Mach numbers less than 4.0, the orbiter entry DAP transitions to a more conventional roll/yaw scheme using the ailerons for roll and the rudder and yaw jets for sideslip control.

The rate of change of the sideslip angle is a negative stability yaw rate ( $\dot{\beta} = -rs$ ).

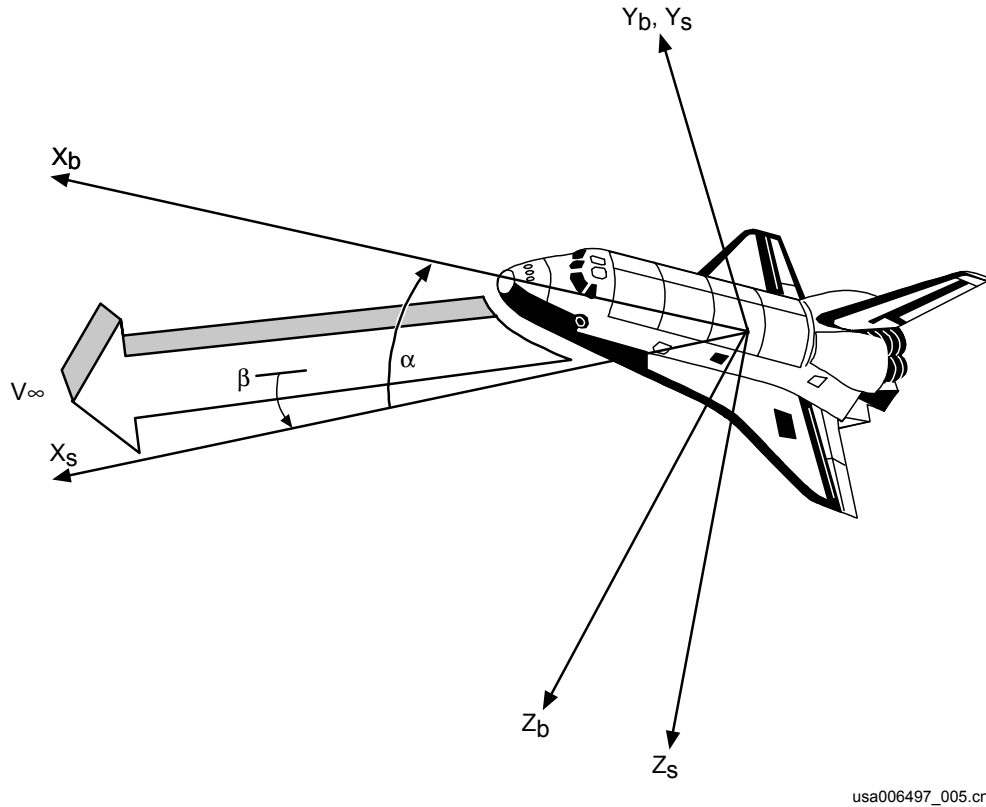
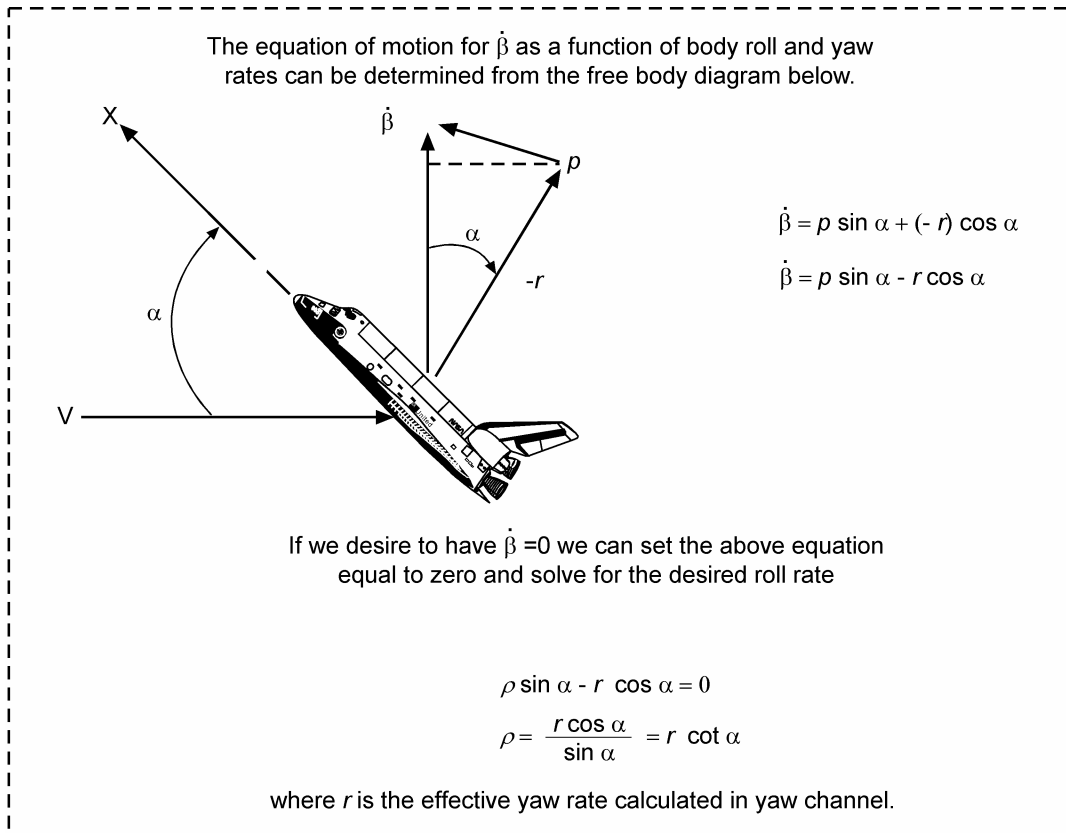


Figure 3-1. The stability axis system

### 3.3 LATERAL-DIRECTIONAL CONTROL

Lateral-directional control of the orbiter is maintained by the combined use of yaw jets, ailerons, sideslip angle, and rudder (when active) to produce bank maneuvers during entry. Although sideslip is intentionally generated during a maneuver, it must be kept within limits to prevent loss of control due to lateral-directional instability. The DAP does this by damping  $\beta$  to zero, using yaw rate feedback to the ailerons.

The bank maneuver is initiated by a bank rate command sent to the yaw channel, resulting in yaw rate command. Bank refers to a rotation about the velocity vector or a stability axis rotation. Roll refers to a rotation about the x-axis or a body axis rotation. Figure 3-2 illustrates how the orbiter yaw rate command is generated.



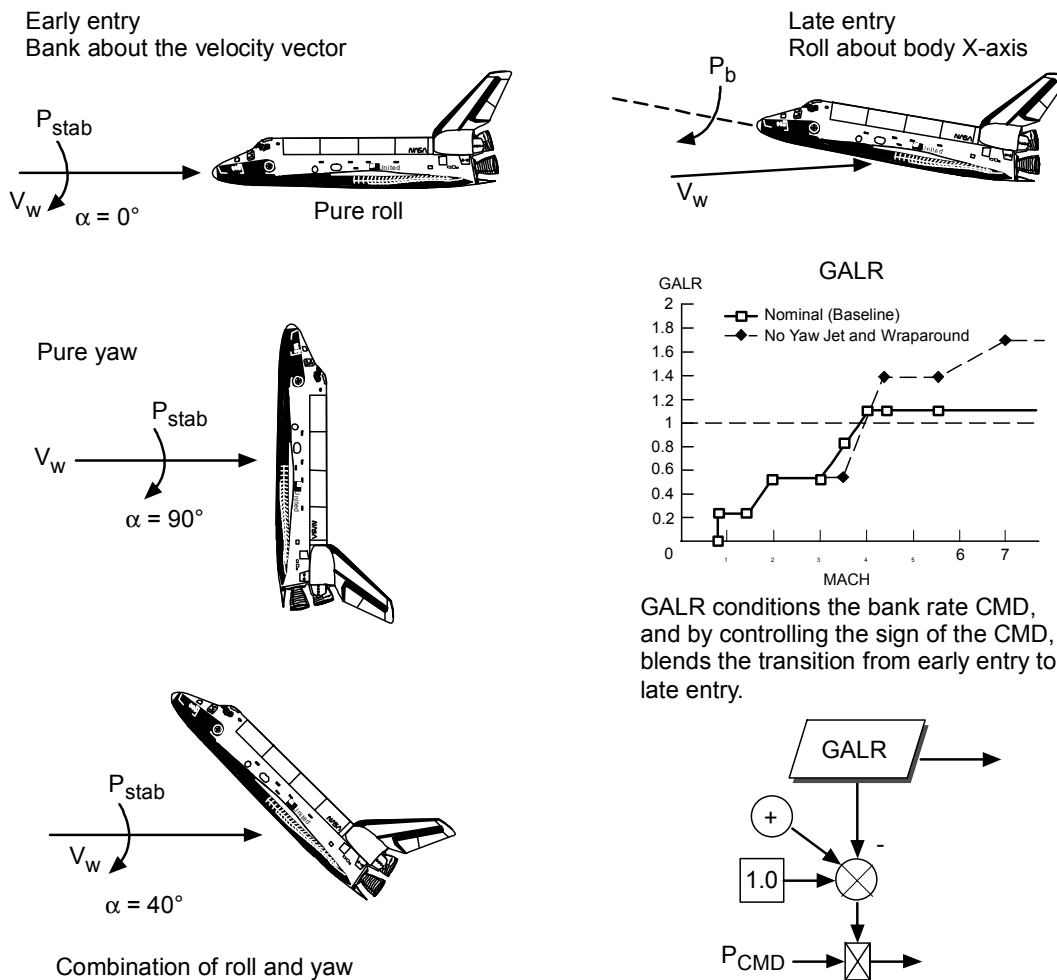
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**Figure 3-2. Orbiter yaw rate command**

To tie all this information together into a coordinated bank maneuver, the lateral-directional control is divided into two regimes, early and late, as was the longitudinal control. The difference between the two regimes for lateral-directional and longitudinal control is the absence of a sharp dividing point separating the early and late lateral control characteristics, as was present in the pitch axis.

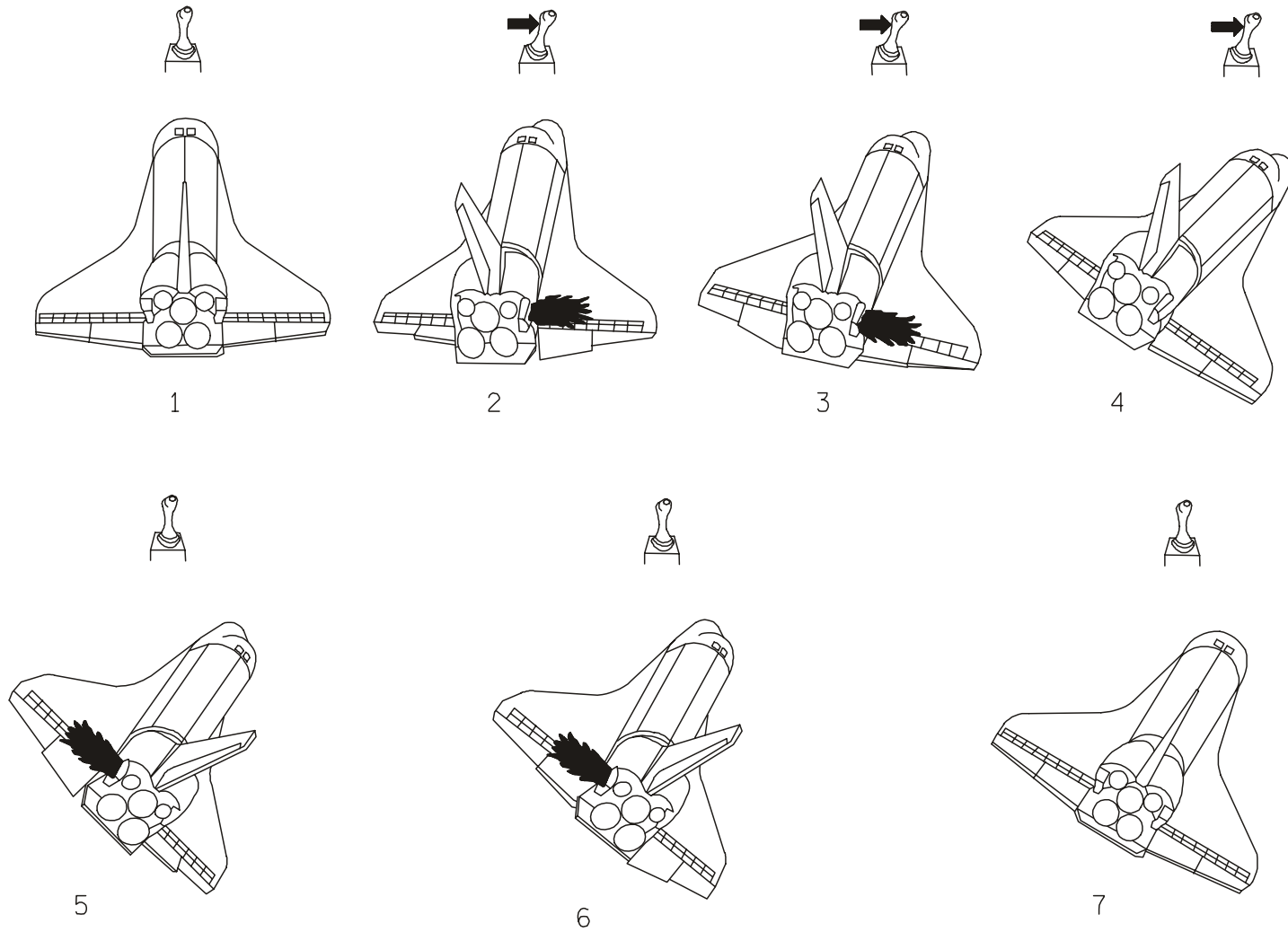
At Mach numbers above 3.5, bank maneuvers are initiated in the yaw channel, and the roll axis provides coordination and damping. As the vehicle aerodynamics are changing below Mach 4.0, there is a gradual change from yaw channel bank maneuver initiation to roll channel initiation, with coordination coming from the yaw channel.

Figure 3-3 shows how the orbiter does bank maneuvers and how this transition is made. In early entry, the orbiter banks about the velocity vector. The figure shows that for zero  $\alpha$ , a stability axis bank is pure body roll, and at  $90^\circ$   $\alpha$ , it is a pure body yaw; for nominal flight alphas, the stability bank is a combination of body roll and yaw. The orbiter rolls about the body X-axis during the late entry. The Gain for Aileron in Roll Channel (GALR) is the mechanism by which the transition from early to late entry is made. GALR conditions the bank rate command and, by controlling the sign of the command, blends this transition. A close view of the bank maneuvers is shown in Figure 3-4.



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Figure 3-3. GALR effects on the orbiter bank



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**Figure 3-4. Chase view of the orbiter bank maneuver**

The following is an explanation of the sequence of events during the orbiter bank maneuver (shown in Figure 3-4) using the Wraparound DAP.

(1) From a steady state  $0^\circ$  bank condition, (2) a right bank maneuver is commanded (CSS). The command ( $p_{cmd}$ ) feeds into the roll and yaw channels where it is turned into rate error signals. The yaw error signal ( $r_{err}$ ) goes to the JSL, and a yaw jet command is issued that initiates the maneuver. The roll command is multiplied by 1-GALR (which results in -0.7 for Wraparound DAP) in the roll channel, which assists in initiating the maneuver by creating a reverse aileron command (right roll, left aileron). This reverse aileron is noticeable in early entry and is subsequently overridden by a positive aileron (right roll, right aileron) command. (3) The body yaw rate created by the reverse aileron and yaw jet firing causes the sideslip to build and is fed to the roll channel for turn coordination. It comes from the yaw channel corrected for steady state rates and is converted into a roll rate command. This is multiplied by GALR (1.7) and summed with  $p_{cmd}$  giving the normal, overriding right aileron for coordinating the left bank command. The combination of roll due to aileron ( $C_{l_{\delta a}} * \delta_a$ ) and roll due to sideslip angle ( $C_{l_{\beta}} * \beta$ ) produces the body roll rate. (4) As the stability roll rate becomes established, its feedback term is differenced with the other roll rate terms to effectively produce a zero roll rate error when the proper body roll and yaw rates have been established. (5) When the RHC is released (assuming CSS), (6) the reverse process occurs, (7) stopping the bank maneuver at the new desired bank angle.

The GALR term for Wraparound DAP and No Yaw Jet is increased over the Baseline DAP for Mach numbers greater than 4.0. Baseline GALR is 1.1 for Mach greater than 4.0. In Wraparound DAP, GALR equals 1.4 for Mach 4.25 to 5.5, increasing to 1.7 for Mach greater than 7.0. This effectively gives primary control authority to the ailerons rather than the yaw jets for Wraparound, and complete control to the ailerons in the case of No Yaw Jet, where the yaw jets are inhibited from firing. With increased aileron gains, the elevons are deflected a greater amount for a commanded maneuver. This results in slight initial roll opposite to the command, which in early entry is noticeable to the crew. Once the sideslip is established due to aileron deflection and yaw jet firings, the ailerons reverse as in Figure 3-4 to control the roll rate. Wraparound DAP is selected as the nominal EOM control mode.

### 3.4 LATERAL-DIRECTIONAL TRIM

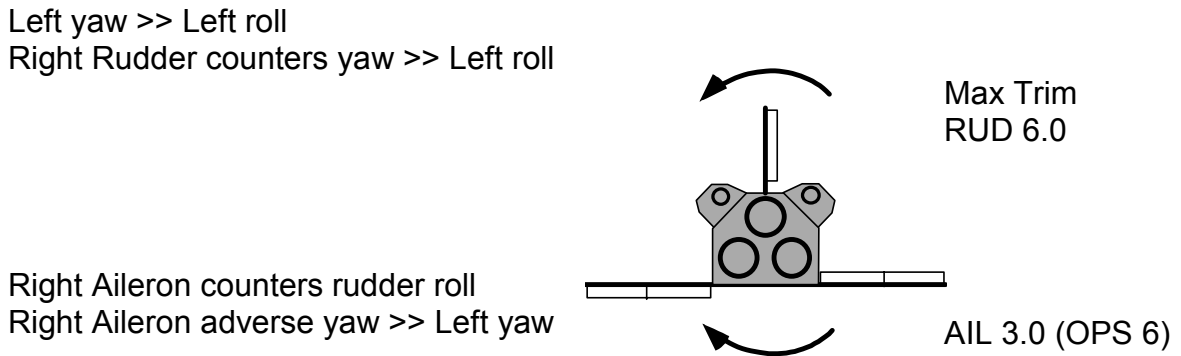
To be trimmed, the aerodynamic moments about an axis or set of axes must be zero. Lateral-directional moments are described in terms of rolling moment coefficient ( $C_{l}$ ) and yawing moment coefficient ( $C_n$ ). Forces acting on a vehicle to create these moments include c.g. offset along the Y-axis, asymmetric aerodynamic forces, and bent airframe (rolling and yawing moments at zero sideslip). The task of trimming the orbiter is to generate a set of control inputs that will balance the moments of the c.g. offset, aerodynamics, and bent airframe. The control effectors for trim are aileron deflection ( $\delta_a$ ), sideslip angle ( $\beta$ ), yaw jets (for Mach greater than 1.0), and rudder deflection (for Mach less than 5.0).

Prior to  $\bar{q} > 0.5$ , when the elevons become active for pitch trim only, lateral-directional trim is left to the RCS jets and sideslip angle. When the elevons are active,  $\bar{q} > 0.5$ , they will be driven to trim the vehicle in response to pitch jet firings only. At  $\bar{q} > 2.0$  the elevons are now fully active for control and trim in all axes. Automatic aileron trim will now drive the ailerons out in response to roll and yaw jet firings, offsetting the moments due to c.g., asymmetric aerodynamics, and bent airframe, stopping the jet firings.

The rudder becomes active at Mach 5 and, under normal circumstances rudder deflection ( $\delta_r$ ) will assume a large portion of the lateral-directional trim function. A trim solution can go from aileron deflection ( $\delta_a$ ) and  $\beta$  to rudder and  $\beta$  or to a combination of aileron, rudder, and  $\beta$ . Normally, the  $N_y$  feedback in the yaw channel will drive the rudder trim to remove sideslip angle, resulting in a trim solution of aileron and rudder. Until Mach number reaches 1.0, the yaw jets are still available. There is no unique trim solution, and any combination of control effectors within their individual limits is possible.

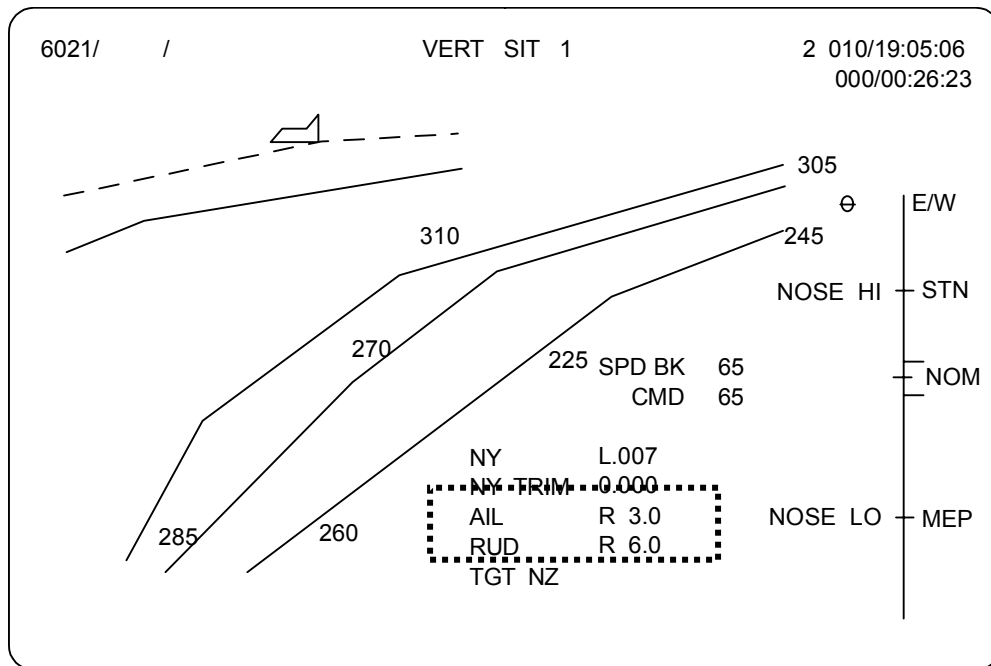
From all of the possible trim solutions available when the rudder becomes active, there are a few unlikely solutions that can be troublesome if they occur.

A particularly bad situation results from a combination of aileron and rudder trim deflections. This is referred to as an aileron-rudder force fight (Figure 3-5). As the ailerons and rudder move to trim the vehicle, their combined effects can be partially or totally offsetting. Essentially, the rudder drives out, creating the desired yawing moment, but also a rolling moment opposite to the rudder deflection (right rudder  $\rightarrow$  left roll). The ailerons trim out to counter the rolling moment, creating an adverse yaw (right aileron, left yaw), which the rudder then tries to trim. The rudder again creates the desired yawing moment, but also the opposite rolling moment, and so on. If each one fights the other, they will be driven to their respective limits ( $3^\circ$  or  $5^\circ$  for aileron,  $6^\circ$  for rudder), making it necessary for jets and the sideslip angle to complete the trim solution. Possible results are an excessive use of RCS propellant, a reduction in maneuvering capability (especially in the event of yaw jet failure) and, in some cases, a loss of control of the vehicle.



**Figure 3-5. Aileron-rudder force fight**

If a force fight develops and the crew is monitoring their displays, the crew can intervene. A force fight can be detected on the ENTRY TRAJ or VERT SIT displays (both display aileron and rudder trim) when both the aileron and rudder trim are driving out to the maximum, in the same direction. See Figure 3-6. The values are the actual content of the trim integrators in the software. It must be remembered that it is best to not try to infer trim from the SPI. The SPI shows the combined value for trim and control deflection. It is safe to allow some small amount of trim, but if aileron trim equals or exceeds 3.0° with aileron and rudder active, trim the ailerons to zero with the roll panel trim switch and allow the rudder and sideslip angle to provide the trim. Monitoring is necessary because, once trimmed out, the force fight can creep back in under certain conditions.



**Figure 3-6. Aileron-rudder trim showing force fight**

Things to remember about an aileron-rudder force fight:

- a. It can occur, but is highly unlikely, with nominal aerodynamics under certain flight conditions. It is more likely to occur on a contingency abort entry during low mach, high alpha flight.
- b. As the aileron and rudder each move to trim, their effects may be offset, driving each toward its limit, both in the same direction, left or right.
- c. Sideslip angle and jets are required to complete the trim solution.
- d. It will use excessive amounts of RCS fuel.
- e. It can result in a loss of control.

Aileron-rudder force fights are unlikely, but if one occurs, there is a solution. The aileron, in the event of a problem, can be manually driven opposite to the direction of trim, toward zero, with roll panel trim. This forces the rudder to assume major responsibility for trim, breaking the force fight.



## QUESTIONS

1. Describe the stability axis system.
2. Describe the process of controlling lateral direction when sideslip is generated.
3. Describe the difference between early and late regions of lateral-directional control.
4. Describe the significance of GALR.
5. What condition(s) must be satisfied for the shuttle to be trimmed?
6. List the lateral-direction control effectors for trim.
7. State when the rudder becomes active for trim.

## 4.0 ROLL CHANNEL

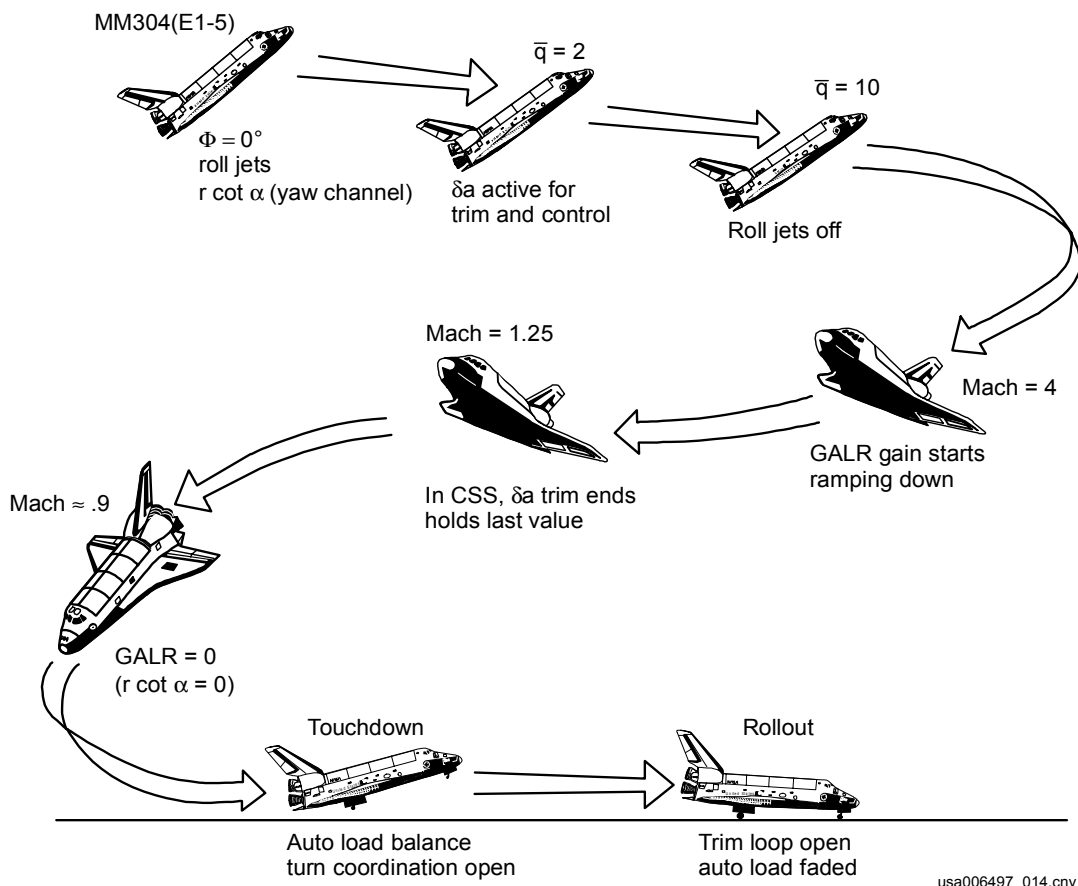
### 4.1 OBJECTIVES

At the end of this section, the student will be able to do the following:

- State when the roll jets are deactivated.
- State when the ailerons are active for control.
- State the consequences of GALR decreasing from 1.1 to 0.0.
- Describe auto load balancing.

### 4.2 INTRODUCTION

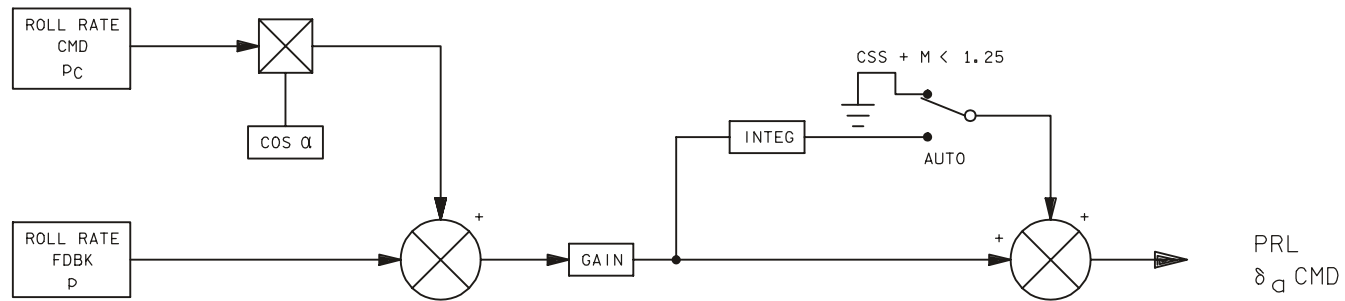
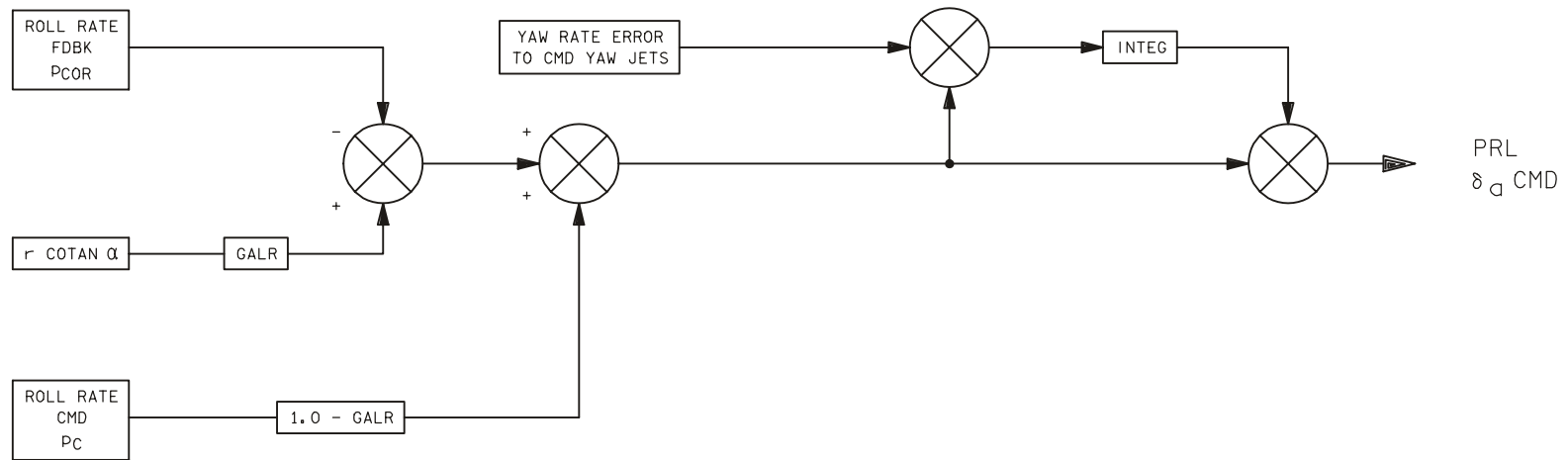
Figure 4-1 shows the major events of the roll channel in a manner similar to that of the pitch channel in Figure 2-1. Beginning at EI - 5, each event peculiar to the roll channel is shown in relation to the other events. These are discussed in detail in the following sections.



**Figure 4-1. The major events of the roll channel**

Figure 4-2 shows the basic schematic of the early and late entry roll channels. Early control is basic turn coordination with rate feedback and proportional command, plus a forward loop trim integrator. The late entry control is a proportional rate command with feedback loop similar to the pitch channel.

For early entry, roll axis is basic turn coordination ( $\beta$  damping) into a proportional plus integral roll rate command system.



For late entry to subsonic flight, roll axis is roll rate command system with turn coordination (proportional for CSS).

**Figure 4-2. Basic schematic of early and late entry roll channels**

The paths of the RHC bank command are shown in Figures 4-3 through 4-7. The command, after being shaped, goes first to the yaw channel and then through various gains (remember GALR) out to the roll jets (until  $\bar{q} = 10$  psf) and the ailerons, which become active at  $\bar{q} = 2$  psf.

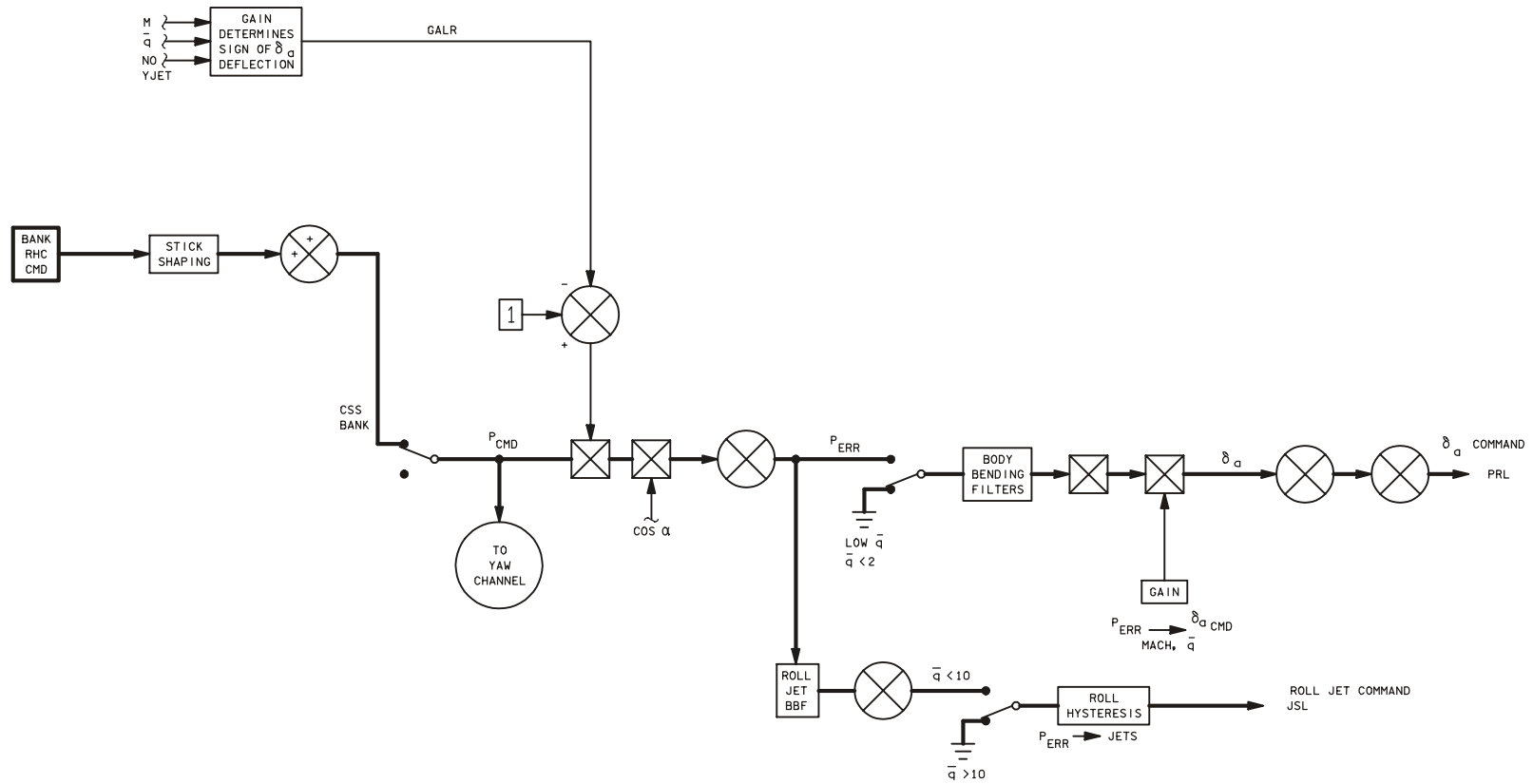


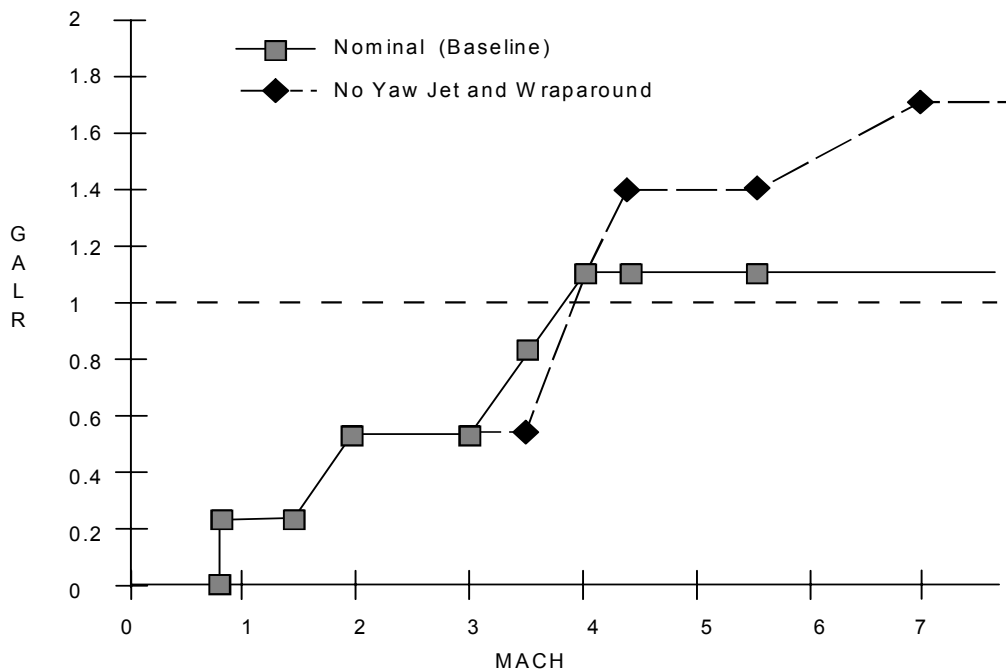
Figure 4-3. The roll channel

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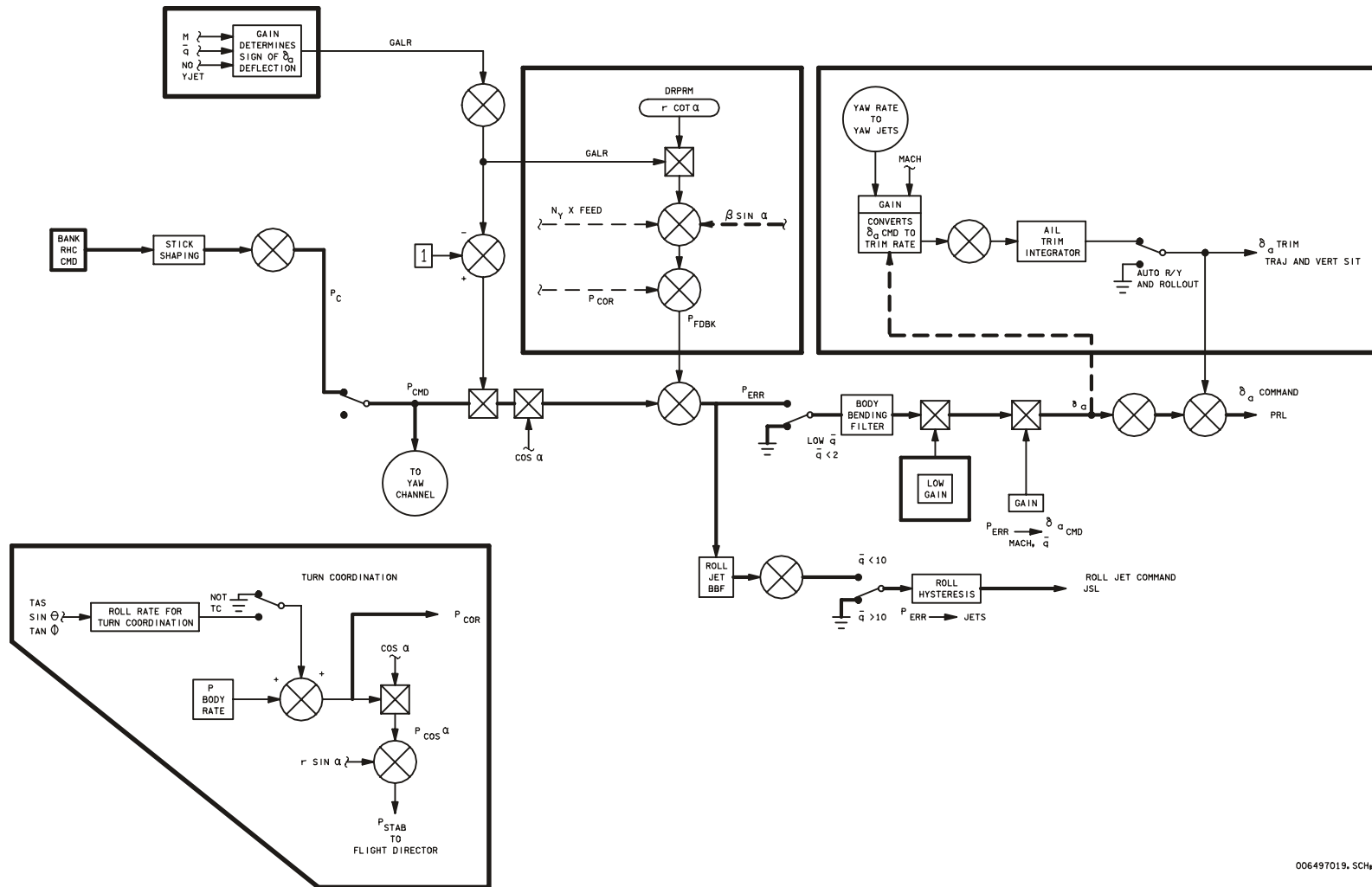
Figure 4-5 introduces the roll rate for turn coordination, calculated and added to the body roll rate, giving corrected roll rate feedback term in roll channel ( $P_{COR}$ ). The yaw rate feedback term from the yaw channel (DRPRM) is then multiplied by  $\cot \alpha$  and by GALR, and is then differenced with  $P_{COR}$ .  $P_{COR}$  and DRPRM make up the primary drivers of the roll rate feedback.

Two additional terms contribute to the roll rate feedback to fine-tune the system and to limit the growth of the sideslip angle. They are both sideslip-dependent terms and operate in a mutually exclusive manner. At  $\bar{q}$  less than 2 psf, this feedback is inertial  $\beta$ ; between a  $\bar{q}$  of 2 to 40 psf, it is filtered inertial  $\beta$ ; and at  $\bar{q}$  greater than 40 psf, it is the lateral acceleration,  $N_y$ . Both  $\beta$  and  $N_y$  terms come from the yaw channel.

The GALR gain, shown in Figure 4-5, goes directly to multiply the DRPRM term and is subtracted from the quantity 1 before multiplying the commanded roll rate. In early entry, this difference creates a small, negative value that acts upon the commanded roll rate to produce the initial reverse aileron. The value of the gain begins decreasing at Mach 4.0, and at about Mach 3.8, it will equal 1.0. A roll rate command is for an instant multiplied by zero, but as Mach number further decreases, so does the value of GALR; therefore, the roll rate command is becoming increasingly positive and dominant in determining the aileron response. Through GALR gain reductions, the aileron response is transitioning from the early entry system of primary  $\beta$  damping about the stability axis to performing conventional roll maneuvers about the body axis in the late entry system.



**Figure 4-4. GALR – Gains for ailerons in the roll channel**



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Figure 4-5. The roll channel – GALR gain



Two things are happening with the reduction of the GALR gain. The magnitude of the gain applied to the commanded roll rate gets larger in a positive sense until it reaches 1.0. This gives the conventional initial aileron response with respect to an input command for late entry (right roll command = right aileron). Secondly, as GALR approaches zero, the effect of the yaw channel input (DRPRM) is being removed from the roll channel.

One input item of the GALR gain loop is NO Y JET. This is a downmoding condition that is selected by the entry mode switch. Selection of this position grounds the command to the yaw jets and changes the value of the GALR gain. The value of GALR before  $\bar{q} = 10$  psf is 1.0. Nominally, its value is then 1.1 until Mach = 4.0, where it begins its ramp down to zero. If in Wraparound or No Yaw Jet, the value of GALR will be 1.7 until Mach = 7, when it ramps down to zero by Mach = 0.9.

Figure 4-6 also shows the aileron trim integrator loop. Aileron trim of the orbiter is accomplished by bringing the yaw rate commands being sent to the yaw jet hysteresis loop into the aileron trim loop. These are summed with the roll panel trim command and integrated. The ailerons take over the trim being done by the yaw jets at a  $\bar{q}$  of 2 psf. This loop is active in the automatic mode until rollout, but when flying in CSS in the roll/yaw axis, the loop opens at Mach 1.25 and holds the last computed value of aileron trim fixed. This is important to remember when flying manually. The pilot may become aware of having to hold a constant roll command when flying around the HAC or down the final approach path. If the roll bias is encountered, simply trim the aileron with the RHC roll trim switch (beep trim).

As in the pitch channel, a low-gain multiplier is available. Whenever the low gain position of the entry mode switch is selected, the gain being applied to the rate error aileron command is cut in half.

Information for crew displays comes from two locations in the roll channel. The body roll and yaw rates are combined to give the stability roll rate, which is sent to the bank rate needle of the ADI. The output of the aileron trim integrator is sent to the ENTRY TRAJ and VERT SIT displays and provides the crew with a direct readout of aileron trim.

The roll panel trim switch is introduced in Figure 4-6. This trim switch, when activated, sends a signal to be summed with the yaw jet rate commands in the aileron trim integrator loop and can drive the aileron directly for trim purposes. The limits on aileron trim are  $\pm 3^\circ$  for Baseline DAP and  $\pm 5^\circ$  for Wraparound and No Yaw Jet. The roll panel trim switch can be used to trim the vehicle in roll and is much faster than the auto trim function.

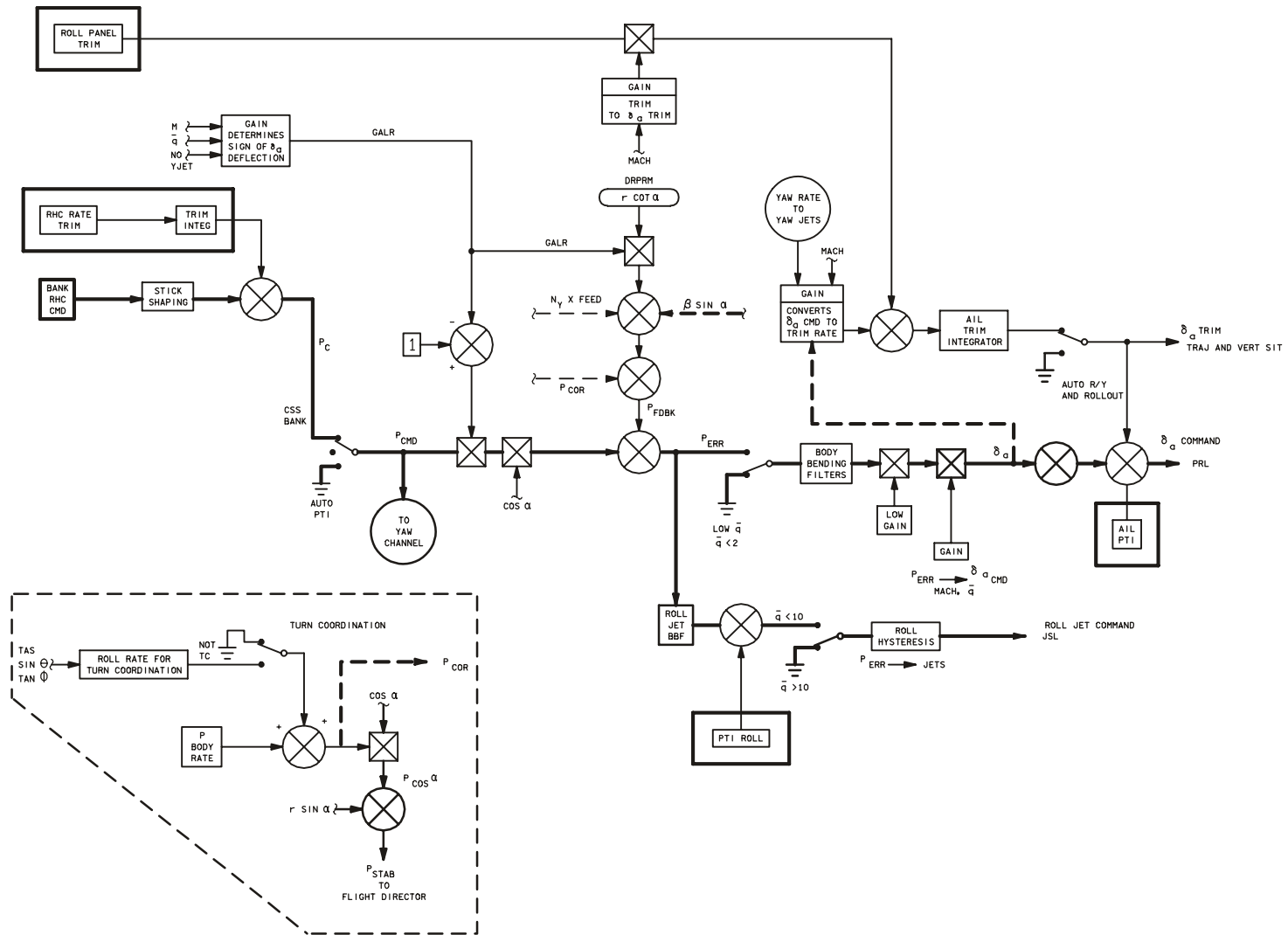
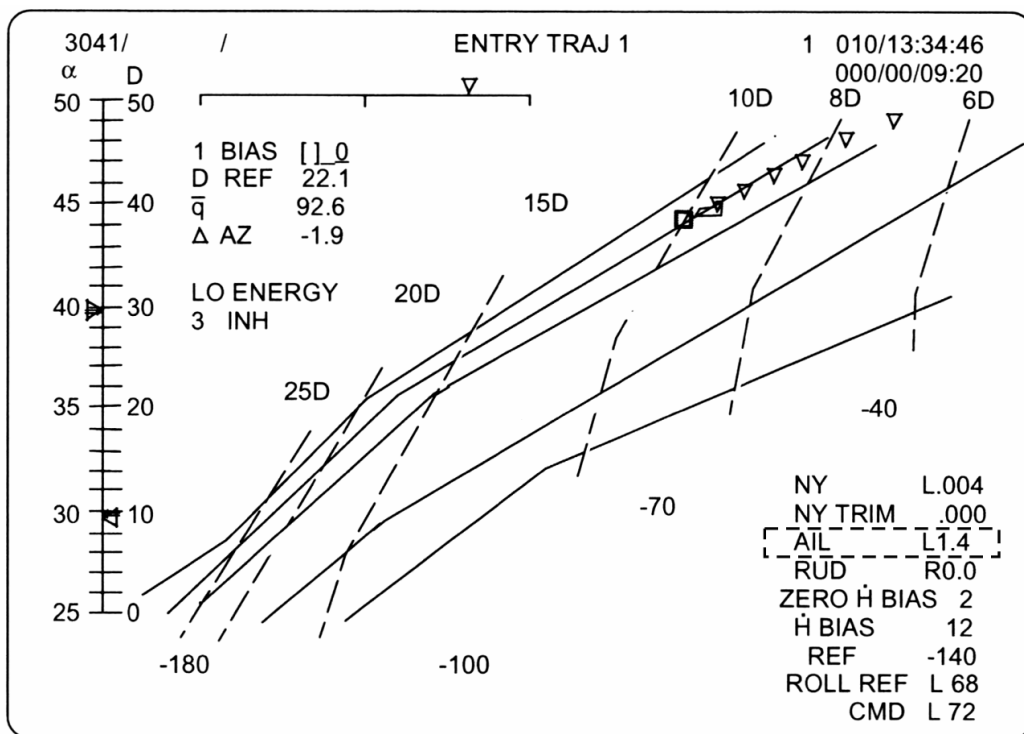


Figure 4-6. The roll channel – panel trim switch

If a lateral trim problem occurs, such as a large offset in the Y c.g., the indications and procedure would be as follows: As the vehicle starts picking up effects of the atmosphere during entry with a  $\Delta y$  c.g. offset, a noticeable increase in yaw jet firings on one side, the side toward which the c.g. is offset, would begin. The offset is causing the vehicle to fly with a sideslip angle for trim, and the jets are firing to control the magnitude of the sideslip and to maintain trim. The RCS jet activity lights would be pulsing, showing commands to fire. At a  $\bar{q}$  of 2 psf, when the ailerons become active, these jet firing commands from the yaw channel cause the aileron to trim out the offset by trimming out the yaw rate error.

The amount of aileron trim required can be seen on the trajectory display, as shown in Figure 4-7.



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**Figure 4-7. The roll channel – ENTRY TRAJ 1 display**

The RHC rate trim switch (beep trim), similar to the pitch channel, provides a bias of up to 2.5 deg/sec on the roll rate command coming from the RHC. This switch functions only in CSS Roll/Yaw (R/Y). A roll rate bias may be removed by use of the beep trim switch opposite to the bias or immediately, and most effectively, by going back to Roll/Yaw Automatic mode (AUTO R/Y).

The PTI modifications to the roll channel are also shown in Figure 4-6 and provide direct commands to the control effectors, as described in the pitch channel.

The automatic control loop is shown in Figure 4-8. In the automatic mode, the bank angle is being commanded by guidance. This command is compared to the actual bank angle of the vehicle; from the resulting difference, a bank command is derived.

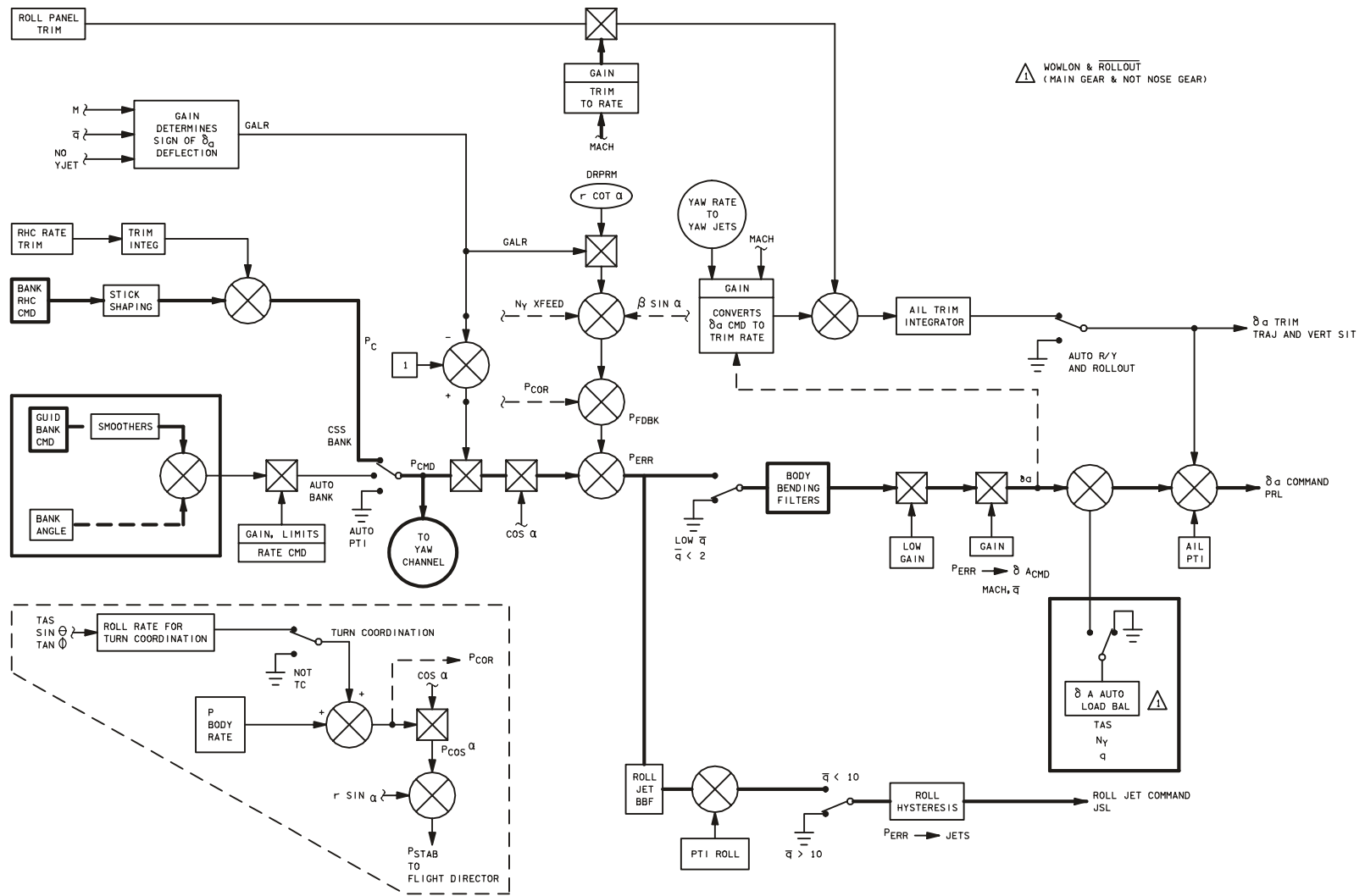


Figure 4-8. The roll channel – automatic control loop

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Following touchdown, the ailerons begin to receive commands attempting to balance the loads between the main tires. This command is based on true airspeed,  $N_y$ , and the yaw rate. It is designed to prevent an imbalance in the main tire load that might be present because of a crosswind during rollout. The lateral acceleration and the yaw rate are a function of the sideslip angle resulting from the crosswind, and they create an aileron command to roll into the wind in an attempt to reduce the sideslip angle. In CSS R/Y, the crew has enough roll authority to mask any auto load balancing by the entry DAP. At nosewheel slapdown, the last aileron command out of the auto load balancing is faded to zero over a 100-second time period.

### 4.3 ROLL AXIS FUNCTIONS

Feature	Function	Use
GALR	Determines the amount and sign of aileron that is commanded in response to a roll command input	<p>Allows blending of early phase into late phase with a <math>1 - \text{GALR}</math> term. For <math>\bar{q} &lt; 10</math>, GALR is 1.0; that gives only turn coordination in the roll axis and no direct command function. The bank command goes to the yaw axis and generates a yaw rate, which feeds the roll axis turn coordination. This function commands the proper roll rate to coordinate the stability axis bank. For Baseline DAP, from <math>\bar{q} = 10</math> to Mach 4.0, GALR = 1.1. This causes a small reverse aileron input in response to bank commands, which improves responses (aids in achieving initial <math>\beta</math>).</p> <p>For Wraparound and No Yaw Jet DAP, from <math>\bar{q} = 10</math> to Mach 7.0, GALR = 1.7, decreasing to 1.4 by Mach 4.25. This gives a large reverse aileron input to achieve the initial <math>\beta</math>. Yaw jets are used to assist the ailerons in achieving the initial rate. From Mach 4.0 to Mach 0.9, GALR goes to zero through a series of ramps and plateaus. This takes the roll channel configuration into the pure late system, where roll commands go to the aileron only.</p>
$P_{\text{COR}}$	Corrects roll rate for vehicle turning	Allows proper turn coordination by removing roll sensed because of vehicle turning.
$\beta \sin \alpha$	Inertial sideslip angle	<b>Active <math>\bar{q} &lt; 2</math>.</b> Inertial sideslip angle is used to command roll rate in a direction to reduce sideslip.

Feature	Function	Use
N <sub>y</sub> crossfeed to roll channel	Lateral acceleration crossfeed	<b>Active when <math>p &gt; 0.5</math> deg/sec.</b> Used to augment lateral acceleration during roll maneuvers to improve damping.
RHC beep trim	Biases RHC roll rate command	<b>Active when CSS.</b> To trim in roll rate, to compensate for RGA bias.
Roll panel trim	Changes aileron position	<b>Active in MM 304, 305.</b> Inputs directly to forward loop trim integrator in auto and CSS (Mach > 1.25). In CSS, Mach < 1.25, the integrator acts as a pure trim device in response to the panel trim switch only.
Aileron trim logic	Provides auto trim function	<b>Active in MM 304, 305.</b> Integrates roll and yaw rate error signals to provide proper aileron trim: 3.0° max for Baseline, 5.0° for Wraparound and No Yaw Jet.

## QUESTIONS

1. When are roll jets deactivated?
2. When are the ailerons active for control?
3. What is the consequence of GALR decreasing from 1.1 to 0.0?
4. Describe auto load balancing.



## 5.0 YAW CHANNEL

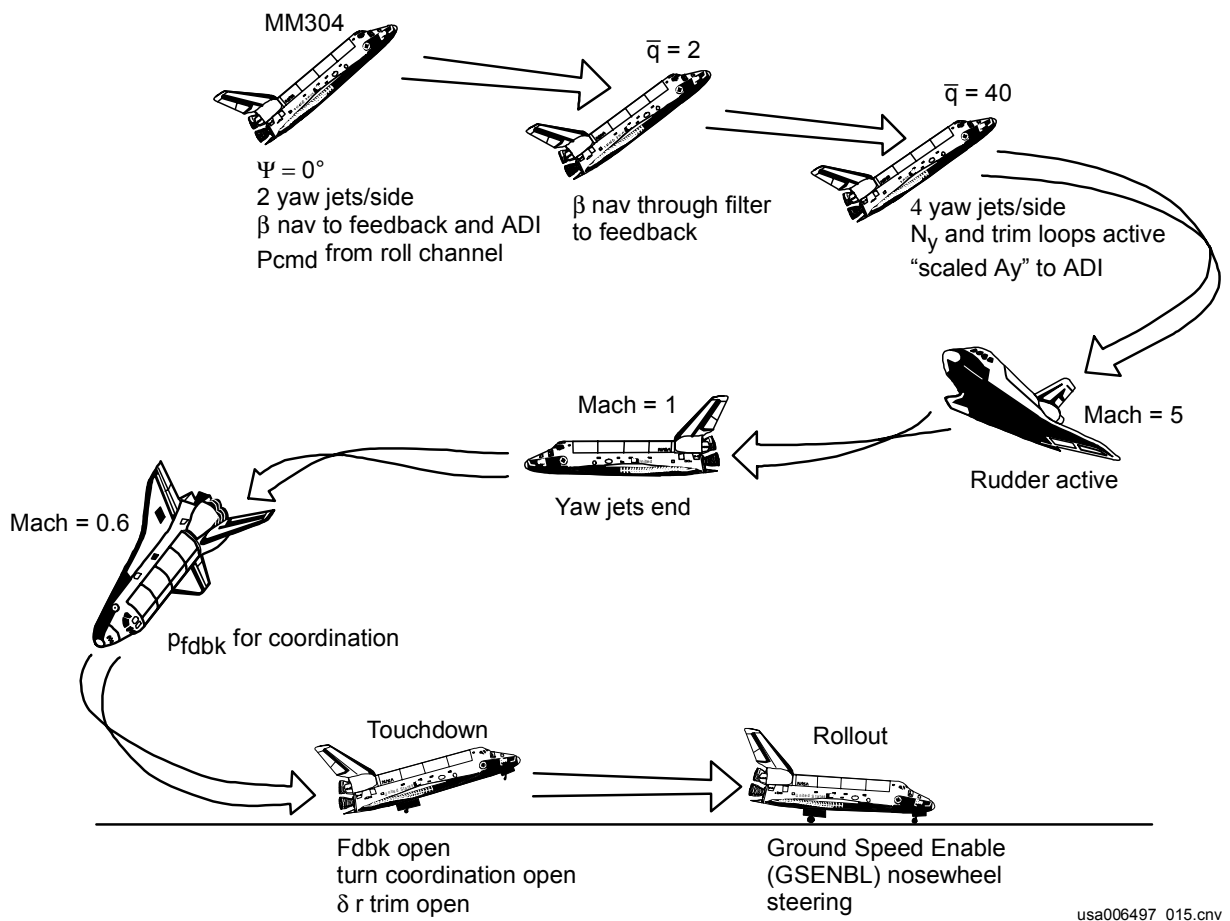
### 5.1 OBJECTIVES

At the end of this section, the student will be able to do the following:

- State the driving parameter in the yaw channel for most of the entry
- State when the rudder becomes active

### 5.2 INTRODUCTION

The major channel events are shown in Figure 5-1. The detailed discussion of the yaw channel that follows expands and clarifies each of the events.



**Figure 5-1. Major yaw channel events**

The yaw channel is a proportional command plus a forward loop trim integrator that provides yaw rate turn coordination,  $\beta$  damping, and sideslip control. A simplified schematic is shown in Figure 5-2.

- a. Bank command from the stability axis is converted to the appropriate yaw rate command via “ $\sin \alpha$ ” and is differenced with yaw rate feedback to generate an error signal.
- b. Lateral acceleration is also used to generate a yaw rate error to reduce  $\beta$ .
- c. The two error signals are summed and multiplied by a gain to generate a yaw jet command and/or a rudder command after it is active.
- d. After rudder activation, the RPTA may be used to bias the lateral acceleration feedback and is thus a lateral acceleration command device and not a rudder command device.
- e. Rudder trim biases the RPTA output.

The beginning logic of the yaw channel is shown in Figure 5-3. For most of entry, the driving parameter in the yaw channel is the bank rate command. This command is multiplied by  $\sin \alpha$  and subtracted from the body yaw rates coming from the RGAs to produce a yaw rate error that goes to the jet select logic to issue yaw jet firings and, for Mach less than 5, rudder commands. The aileron trim information is picked off the rate error path to the yaw jets for use in the roll channel.

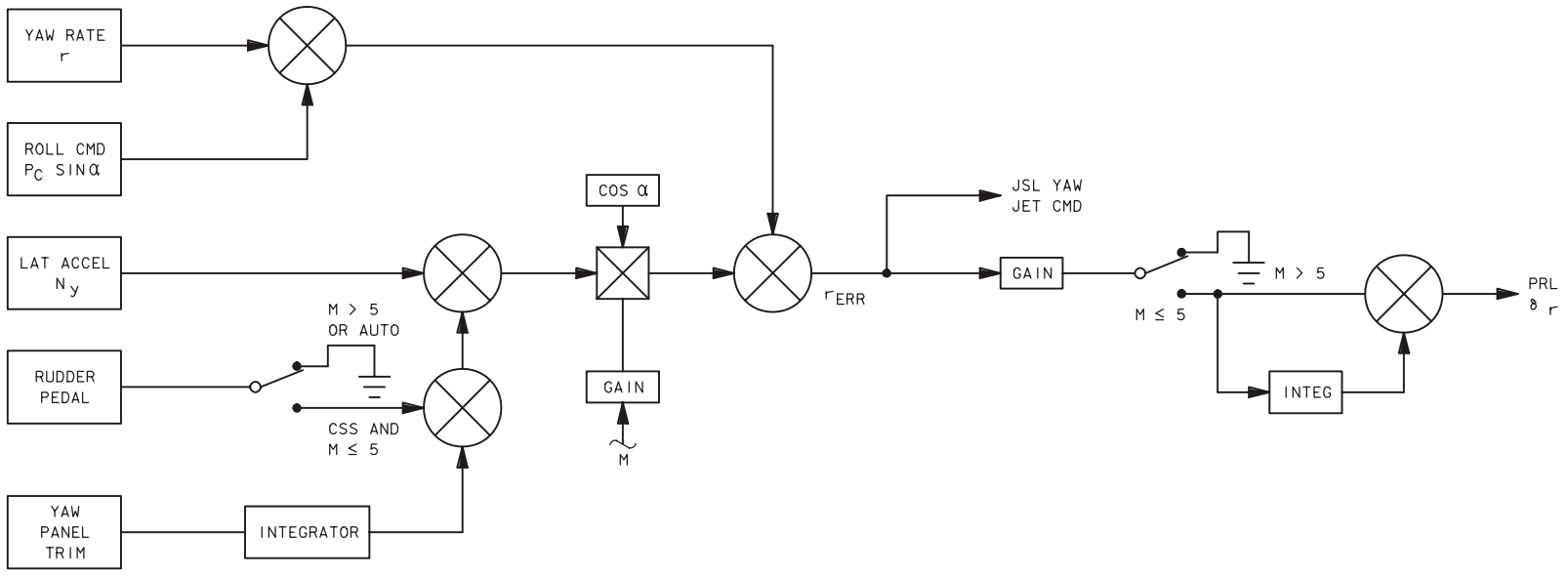
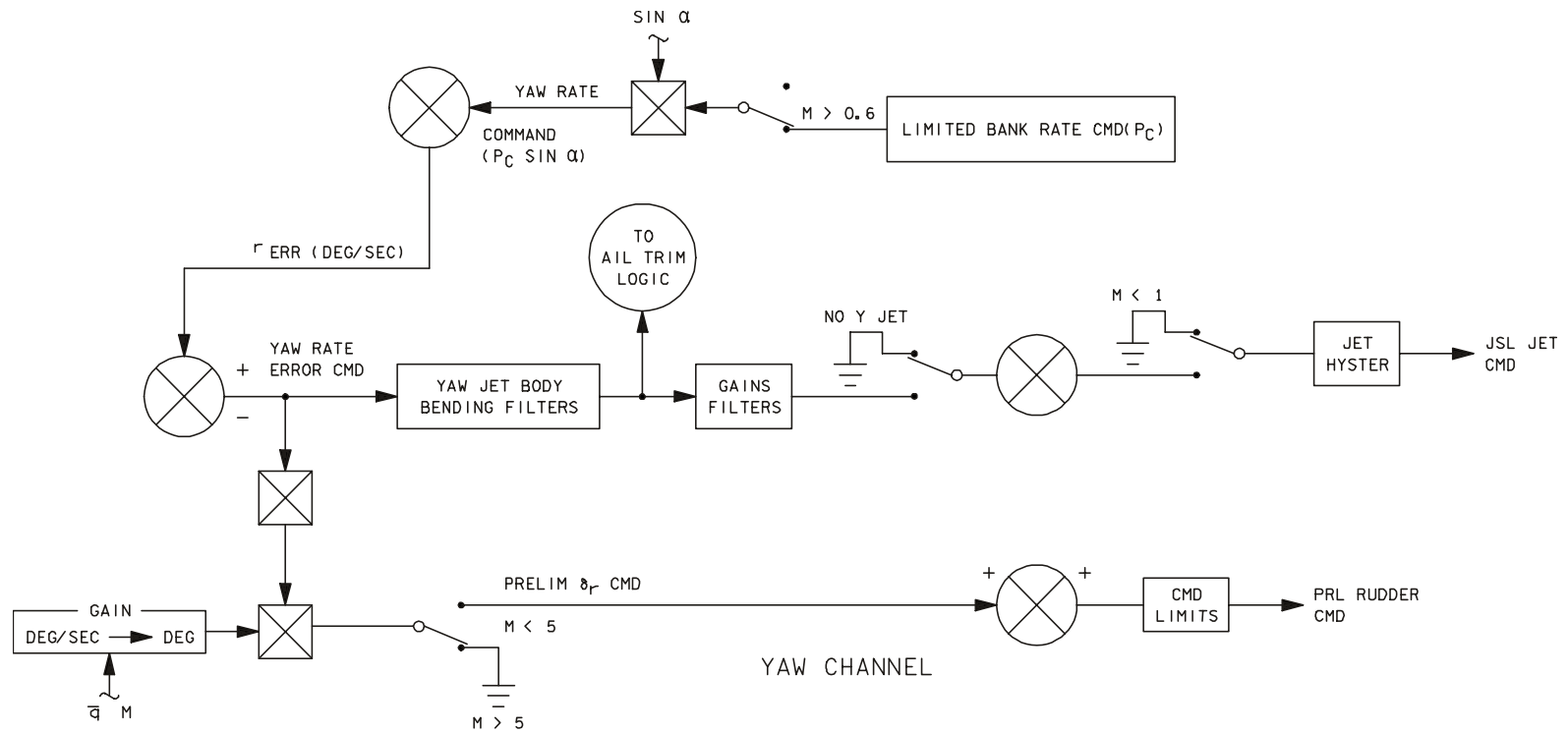


Figure 5-2. Simplified yaw channel

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006497014. SCH, 1

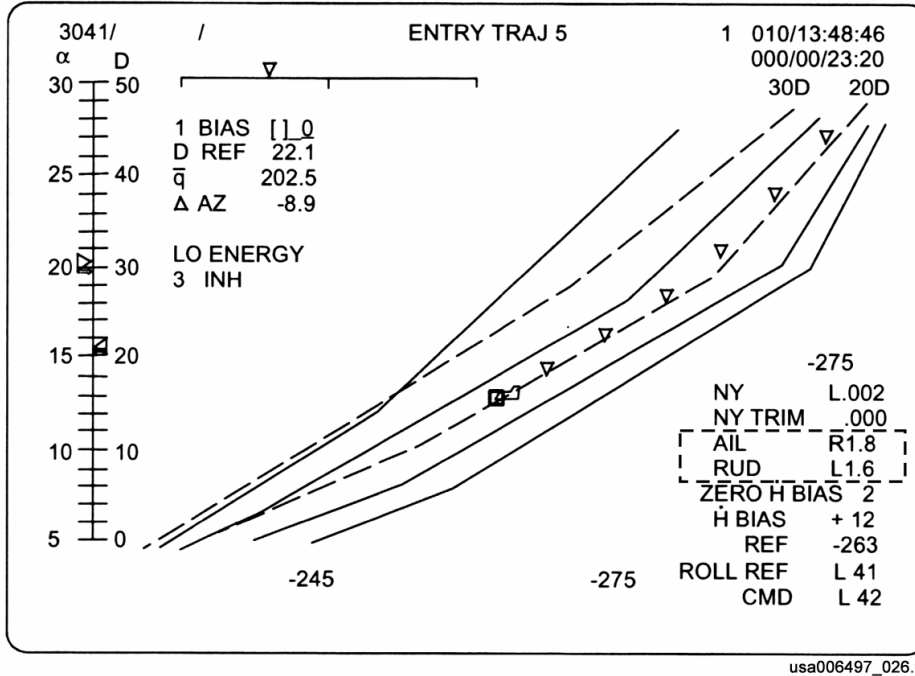
Figure 5-3. Beginning logic of the yaw channel

Figure 5-5 shows how the inertial sideslip angle feedback is used for sideslip control during flight in the low  $\bar{q}$  regime (less than 2 psf). This sideslip angle is used in the roll channel for  $\beta$  control, as previously described, and is also sent to the yaw error needle on the ADI as an indication of sideslip angle to the crew (until  $\bar{q}$  is greater than 40 psf). After  $\bar{q}$  is greater than 2 psf and less than 40 psf, the inertial sideslip angle is in the yaw channel to keep a large transient in  $\beta$  from developing, which might counter the rolling action during the first bank maneuver. This is accomplished by sending inertial beta through a washout filter that effectively removes the steady state value and allows only the transients in the sideslip angle to go through for control purposes. Sideslip angle, filtered or unfiltered, is sent to the roll channel until a  $\bar{q}$  of 40 psf is reached.

When  $\bar{q}$  is greater than 40 psf the yaw channel computes an estimated  $\beta$  or “scaled  $A_y$ ,” which replaces inertial  $\beta$  as the sideslip control term. The estimated  $\beta$  is computed using  $N_y$  in combination with compensation for surface deflections, accelerometer location, jet firings, Mach number, angle of attack, and  $\bar{q}$ . Its accuracy is thus dependent on the modeling accuracy of the aerodynamics and sensors. This yaw rate error based upon sensed lateral accelerations is summed with the corrected yaw rate command to become a command to the jets and rudder. Scaled  $A_y$  is also sent to the yaw error needle on the ADI, replacing inertial sideslip angle.

The yaw rate for turn coordination is shown in Figure 5-5. This term goes to the pitch channel (post-TAEM) for turn compensation. In the yaw channel, it is differenced with the body yaw rate feedback to produce the DRPRM which is used in the yaw channel as the corrected yaw rate feedback and is also used in the roll channel.

The rudder, rudder pedals, and forward loop trim integrator become active at Mach 5, as shown in Figure 5-6. The trim integrators should start taking over some of the lateral-directional trim requirements and partially relieve the ailerons of that function. The crew can check this activity on the ENTRY TRAJ or VERT SIT displays as shown in Figure 5-4. The rudder pedals function strictly as a bias to the lateral acceleration feedback. The crew can make inputs through the pedals and can expect to see an initial rudder movement in the direction of the automatic stability loops. In practice, the orbiter usually is flown with the feet on the floor until touchdown, when braking and steering come into play.



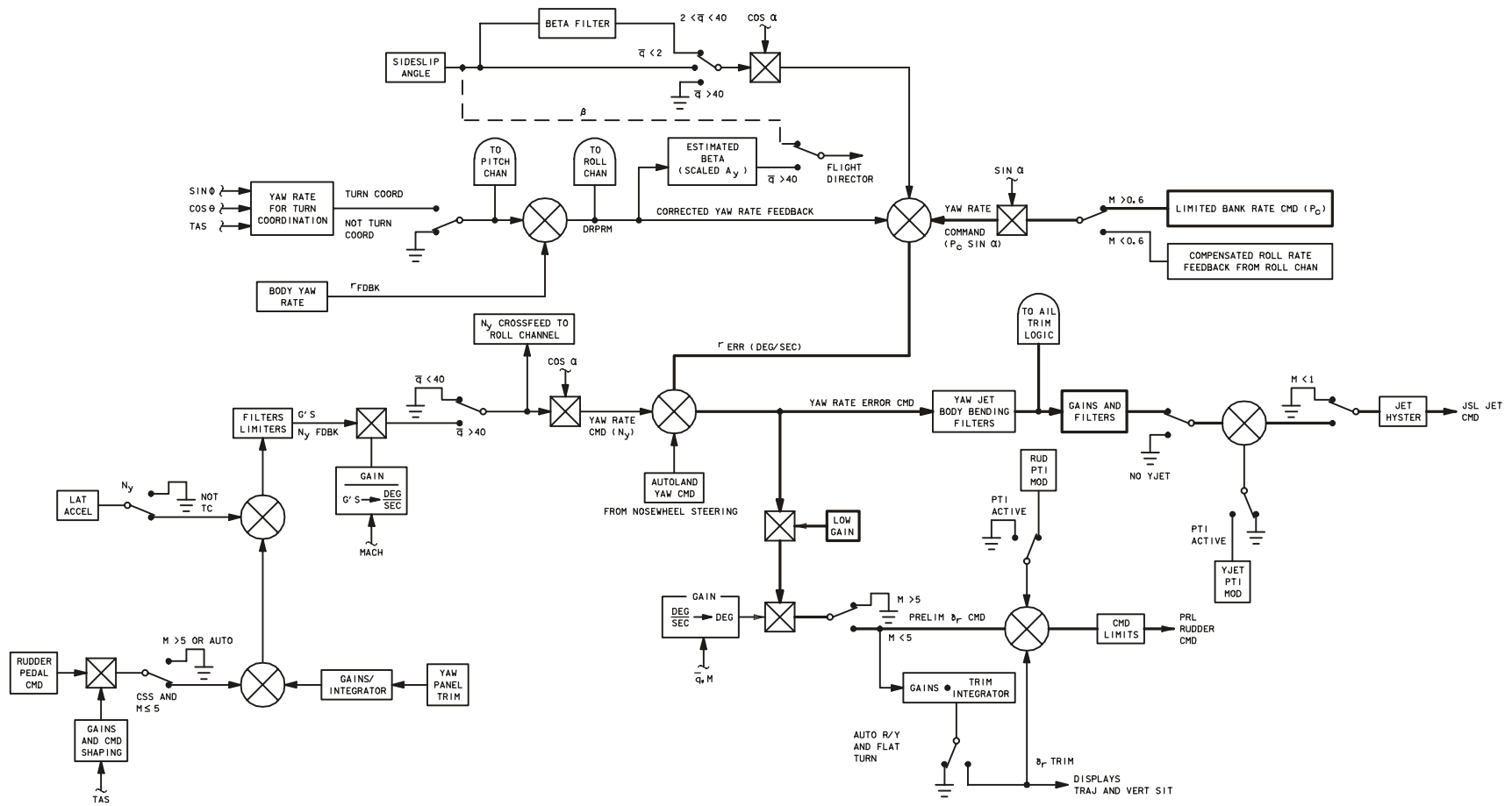
**Figure 5-4. Entry Traj 5 showing aileron and rudder trim**

At Mach numbers less than 0.6, the input changes from the bank rate command to a roll rate feedback term, which is used to coordinate turns.

The autoland yaw commands are sent to the yaw channel when Nosewheel Steering (NWS) is incorporated at nosewheel slatdown. This is an automatic mode that requires AUTO R/Y and a Ground Speed Enable (GSENBLE) flag to be set. Manual NWS is available in CSS R/Y.

The low gain and PTI modifications in the yaw channel are similar to those previously described in the pitch and roll channels.





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Figure 5-6. Complete yaw channel



### 5.3 YAW AXIS FUNCTIONS

Feature	Function	Use
Limited bank rate command	To command jets and rudder in response to RHC inputs	<b>Active Mach &gt; 0.6.</b> Multiplied by $\sin \alpha$ to construct yaw rate command for coordinated stability roll.
Inertial sideslip angle	Limited sideslip in low $\bar{q}$ regime	<b>Active <math>\bar{q} &lt; 2</math>.</b> Maintaining sideslip within allowable limits, yaw component of nav-derived sideslip is converted to a body yaw rate command.
Beta washout filter	Allows flight control to transition from inertial sideslip to measured lateral acceleration	<b>Active <math>2 &lt; \bar{q} &lt; 40</math>.</b> Filters steady state and small transient $\beta$ , while allowing large transients such as the first bank command after closed loop guidance to pass through.
Scaled $A_y$	$\beta$ estimated based on measured lateral acceleration, $N_y$	<b>Active <math>\bar{q} &gt; 40</math>.</b> Computed using lateral acceleration ( $N_y$ ) in combination with compensation for surface deflections, accelerometer location, jet firings, Mach number, angle of attack, and $\bar{q}$ .
DRPRM	To correct yaw rate for vehicle turning	<b>Active in TAEM.</b> Allows properly coordinated turn by removing yaw rate sensed because of vehicle turning.
$N_y$ crossfeed to roll channel	Aids in coordinating roll maneuvers	<b>Active when roll &gt; 0.5 deg/sec.</b> Used to augment lateral acceleration during roll maneuvers to improve damping.
Rudder pedal transducer assembly	Manual rudder flight control	<b>Active Mach &lt; 5.</b> Provides limited manual yaw axis control by biasing the lateral acceleration feedback to the yaw channel. Not required in flight due to automatic turn coordination in AUTO and CSS, the RPTAs are used for manual nose wheel steering during landing rollout.
Compensated roll rate feedback from roll channel	Used to scale yaw rate command	<b>Active Mach &lt; 0.6.</b> Roll rate shipped to the yaw channel is multiplied by $\sin \alpha$ , which converts it to a body yaw rate command to damp $\beta$ .

## QUESTIONS

1. What is the driving parameter in the yaw channel for most of the entry?
2. When does the rudder become active?

## **6.0 LANDING DISCRETES**

### **6.1 OBJECTIVES**

At the end of this section, the student will be able to do the following:

- a. State the actions required in case the Weight on Wheels (WOW) discrettes or the Weight on Nose Gear (WONG) discrettes are not set automatically.
- b. State how load relief is accomplished when landing in CSS P.

### **6.2 LANDING DISCRETES**

The landing of the orbiter is broken into two distinct phases, touchdown and rollout. The touchdown naturally occurs at the moment when the main landing gear contacts the ground, Main Gear Touchdown (MGTD), under controlled conditions. At touchdown, several discrettes are set that prompt changes in the entry DAP. These WOW discrettes, as shown in Figure 6-1, are Weight on Wheels Latched On (WOWLON), FLATTURN, and Heads Up Display (HUD) WOWLON. These discrettes are initiated by two of three main gear sensors: one touchdown proximity sensor, and two wheel speed sensors on either the left or right main gear. Crew initiation of either the External Tank Separation (ET SEP) or Solid Rocket Booster Separation (SRB SEP) switch and pbi, with pitch angle ( $\theta$ )  $< 0^\circ$ , also sets WOWLON. A dilemma will occur if one of the WOW discrettes disagrees with the other for 7 seconds. In a dilemma case, the crew must use the ET SEP or SRB SEP switches and pbis to set the landing discrettes. (However, it would take three or more failures to disable three of the six sensors used to set WOWLON.) WOW also sets the FLATTURN flag, by which turn coordination is ended in all axes. Additionally, WOW reconfigures the HUD for rollout. WOWLON commands the SPBK open to 100 percent and opens the brake isolation valves to make wheel brakes available.

An auto load balance is computed for the ailerons in the roll axis. This is designed to help equalize the loadings on the main tires and gear. The auto load balance command is based on True Airspeed (TAS),  $N_y$ , and the yaw rate. From these sensed parameters, the ailerons are commanded to remove any asymmetric loading on the tires, usually loads resulting from a crosswind, by rolling into the wind to reduce the effect of the sideslip angle.

The rudder trim integration loop is opened at touchdown.

In the pitch axis, ADI pitch rate commands are generated as a function of pitch angle, main gear touchdown, the equivalent airspeed, and the vehicle weight. These rates are converted into elevator commands if in AUTO P mode for automatic derotation at 180 Knots Equivalent Airspeed (KEAS).

Typically the CDR performs derotation using the RHC negative pitch trim switch. This is known as Beep Trim derotation. If the beep trim switch fails, the "manual" derotation is

accomplished in CSS P by moving the RHC forward, negative pitch, and holding a steady derotation rate of  $1.5^\circ/\text{sec}$ .

<b>Initiated by</b>	1. Main gear touchdown	Touchdown discrettes
	or	
	2. Placing ET SEP or SRB SEP switch to MAN and depressing appropriate pbi	WOWLON FLATTRUN HUD_WOWLON
	3. Theta less than $0^\circ$ ( $\theta < 0$ )	
<b>Pitch axis</b>	1. In AUTO P, flight director pitch rate commands generated as a function of $\theta$ , MGTD, KEAS, and weight	
	2. These pitch rate commands are converted into $\delta_e$ commands for auto control before rollout	
<b>Roll axis</b>	1. Auto load balance computed for ailerons, a function of TAS, $N_y$ , and $r$	
	2. $\delta_a$ trim integrator loop is opened (FLATTURN)	
<b>Yaw axis</b>	Opens rudder trim integration input	

**Figure 6-1. Shuttle touchdown discrettes**

Following Nose Gear Touchdown (NGTD), or WONG, rollout discrettes are set by the combination of certain events (Figure 6-2). These are nose gear touchdown itself (one of two proximity sensors), having had WOWLON for 2 seconds, and the pitch attitude must be less than  $0^\circ$  ( $\theta < 0$ ). Setting either the ET SEP or SRB SEP switch with the pbi, again with  $\theta < 0$ , also sets WONG (Figure 6-3). The rollout discrettes include Rollout (ROLLOUT), Ground Speed Enable (GSENBLE), and HUD\_ROLLOUT. WONG also enables NWS and the HUD reconfigures again to display groundspeed rather than airspeed.

In the pitch axis, the elevator trim feedback is grounded (as opposed to having a zero command to the filters). In AUTO P, the elevators will be driven down to assist in relieving the loads on the main landing gear (LOAD RELIEF). If in CSS P, the DAP will mode to AUTO when the load relief flag is set. The elevator position will be commanded to a  $10^\circ$  trailing edge down position, biased by auto load balance commands. CSS pitch can be regained by the "hot stick" method, deflecting the RHC, or by pushing the CSS pitch pbi. If the hot stick method is used, the RHC must be

deflected to nearly the hardstop because the threshold for downmode to CSS opens to 21.7°, from the normal 6°, after LOAD RELIEF is set on.

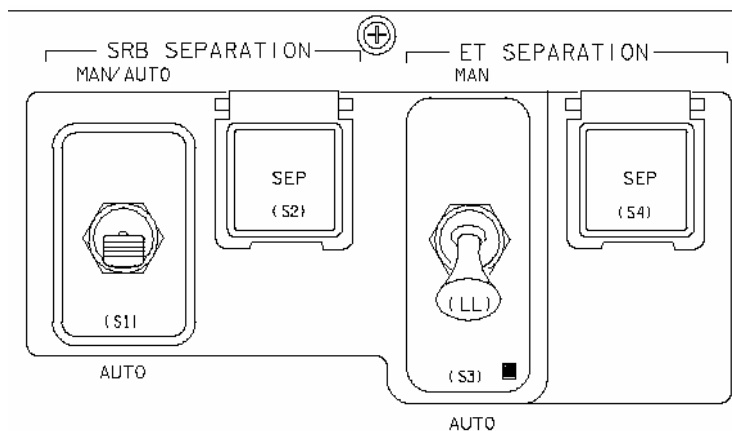
The aileron trim integrator loop is opened at rollout, and the auto load balance command is faded out over a period of 100 seconds.

- Initiated by**
1. Nose gear touchdown
  2. WOWLON for 2 sec
  3. Theta less than 0° ( $\theta < 0$ )  
or
  4. Placing ET SEP or SRB SEP switch to MAN and depressing appropriate pbi
  5. Theta less than 0° ( $\theta < 0$ )

Rollout discretes
WONG
ROLLOUT
GSENL
HUD_ROLLOUT

- Pitch axis**
1. Ground  $\delta_e$  feedback
  2. Automatic (mode to AUTO if in CSS)  
steady state  $\delta_e$  driven to load relief bias
- Roll axis** Auto load balance command faded out over 100 sec
- Yaw axis** NWS with switch in NWS 1 or 2

**Figure 6-2. Shuttle rollout discretes**



**Figure 6-3. SRB and ET separation switches and pushbuttons**

## QUESTIONS

1. State actions required in case the WOW discretetes or WONG discretetes are not set automatically.
2. State how load relief is accomplished when landing in CSS P.

## 7.0 NOSEWHEEL STEERING

### 7.1 OBJECTIVES

At the end of this section, the student will be able to do the following:

State the requirements to set the GSENLB flag and to activate NWS.

### 7.2 INTRODUCTION

NWS is functional in the yaw axis. NWS is available in both the manual (CSS R/Y) and automatic modes. It becomes active when the GSENLB flag is set. This flag requires 2 seconds of having the WOW flag set, the pitch angle ( $\theta$ ) less than zero, and the WONG flag set. GSENLB can also be triggered if the ET SEP switch is set to MAN or the SRB SEP switch is set to MAN/AUTO, the pbi is pushed, and  $\theta$  is less than zero. It is possible, but highly undesirable, to manually set WOW/WONG while airborne.

NWS is powered through the right DDU and the PLTs flight controller power switch. The flight controller power switch, on Panel F8, must be ON, as noted on the Entry Maneuvers cue card (Figure 9-1).

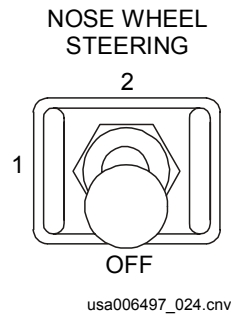
There are three choices for the type of NWS available, and the choice is made with the positioning of the NWS switch on Panel L2 (Figure 7-1).

- a. In the OFF position, no steering commands are accepted; the nosewheel simply casters. Steering is accomplished with rudder and differential braking.
- b. With the switch in NWS 1, the steering can be either automatic or manually accomplished. The choice of automatic or manual is selected by pushing the roll/yaw pbi for AUTO R/Y or CSS R/Y. Typically, steering is done manually by the CDR in CSS R/Y. If NWS should fail, differential braking is an acceptable method for steering the vehicle.
- c. NWS 2 is functionally equivalent to NWS 1. The only difference is the path the commands take from the RPTA through the Data Processing System to the nose gear.

The NWS schematic is shown in Figure 7-2. The nosewheel command is a result of the rudder pedal inputs when the orbiter is being operated in CSS R/Y. In NWS 1 or 2, rudder pedal movements are read by the RPTA and fed into Subsystem Operating Programs (SOPs) in the General Purpose Computers (GPCs). These SOPs bias the commands based on lateral acceleration feedback in order to prevent overcontrol. This also aids initial steering commands in response to tire failures. This provides the best control and handling qualities and is the most favored mode of control. NWS will also respond to asymmetric braking inputs. If the crew commands differential braking with no rudder/NWS inputs, the NWS responds to the sensed  $N_y$ , in effect fighting against the differential braking. When using differential braking, the crew should also command

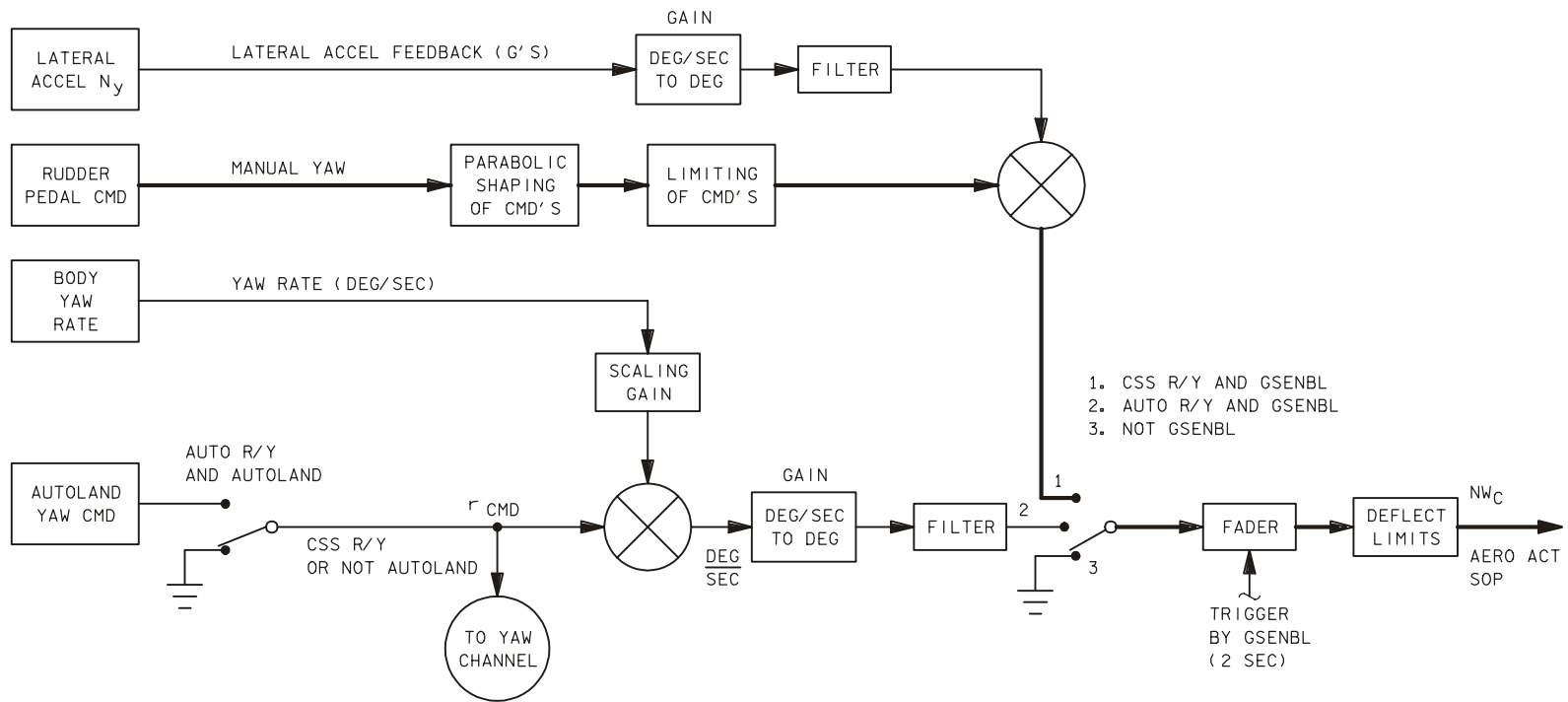
some RPTA deflection in the direction of braking to “command” a yaw rate in the direction of braking.

In the AUTO R/Y mode, with NWS 1 or NWS 2 selected, the yaw rate command is sent to the yaw channel for rudder commands, is differenced with the body yaw rate feedback, sensed as lateral acceleration,  $N_y$ , and becomes a NWS command after passing through the proper gains. AUTO R/Y will steer the orbiter along the runway centerline, determined by the orbiter state vector, using runway coordinates and heading stored in the navigation software. NWS will also respond to crosswind effects.

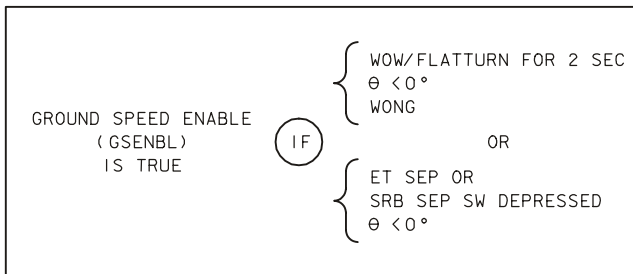


**Figure 7-1. Nosewheel steering switch (Panel L2)**





LANDING SOP:



006497016. SCH, 1

Figure 7-2. Nosewheel channel

## QUESTIONS

1. When is NWS active?

## 8.0 EVENT CHRONOLOGY

### 8.1 OBJECTIVES

At the end of this section, the student will be able to do the following:

- a. State when the aerojet DAP is initialized.
- b. State when the RCS activity lights reconfigure.
- c. State when the roll, pitch, and yaw jets are deactivated.

### 8.2 EVENT CHRONOLOGY

Following is a list of major milestones for entry DAP.

#### EI-5

The aerojet DAP is initialized with the crew keyboard entries of OPS 304 Proceed (PRO). Generally, the control mode is AUTO in all axes, the control surfaces are neutral (flight dependent), command capability for roll, pitch, and yaw jets is available. A roll/pitch/yaw attitude of  $0^\circ/40^\circ/0^\circ$  is commanded. The maximum rates that can be commanded are  $\pm 3$  deg/sec in AUTO R/Y and  $\pm 0.5$  deg/sec in AUTO P. In CSS, the crew can command  $\pm 6$  deg/sec and  $\pm 2.88$  deg/sec in roll and pitch, respectively.

#### $\bar{q} = 0.5$

At a  $\bar{q}$  of 0.5 psf, the elevators become active for trim in response to the pitch jet firings. In this region, the yaw jets are used to start the bank maneuvers, with the roll jets being used for coordination and to damp  $\beta$  during the maneuver.

#### $\bar{q} = 2$

The elevators become active for control. They respond immediately to pitch commands.

The ailerons become active for trim and control. They respond directly for trim, which is being driven by the yaw jet firings, and indirectly to roll command. It is in this region that bank control is being affected by the yaw and roll jets.

At this junction, the inertial sideslip angle is removed as a direct feedback in the yaw channel. It is, however, sent through a washout filter that allows the DAP to correct for transients in the sideslip angle and is displayed on the yaw error needle of the ADI.

#### $\bar{q} = 8$

The elevators no longer respond to pitch jet firings for trim.

### $\bar{q} = 10$

The roll jets are terminated. The ailerons are now responding directly to roll rate commands. From this point until  $\bar{q} = 50$ , the RCS roll activity lights are not active.

GALR increases from 1.0 to 1.1 for baseline DAP. This provides a small reverse aileron command to coordinate the stability axis bank maneuvers. Wraparound DAP becomes active, if enabled, which increases GALR to 1.7, increasing elevon deflection commands and decreasing yaw jet activity.

### **Mach = 23.5**

AUTO R/Y rate increases to 5 deg/sec.

### $\bar{q} = 40$

The pitch jets are terminated. From this point until  $\bar{q} = 50$ , the RCS pitch activity lights are not active.

The number of yaw jets per side available increases to four.

The elevator position feedback trim replaces the forward loop trim integrator loop.

Scaled  $A_y$ , or measured lateral acceleration, replaces inertial sideslip angle in the yaw and roll channel. Scaled  $A_y$  is now displayed on the yaw error needle of the ADI.

### $\bar{q} = 50$

The RCS activity lights are reconfigured (Figure 8-1 and Table 8-1). The pitch jet lights indicate when the elevon rate limit has been saturated. The roll and yaw jet lights work together to indicate how many yaw jets are being commanded to fire in response to a bank maneuver input. A single yaw jet light alone (left or right) indicates the command direction to fire two yaw jets, and the yaw plus roll jet lights indicate three or four yaw jets being commanded on.

### **Mach = 10**

The SPBK begins to open according to its programmed schedule. The SPBK position is fed back into the pitch axis, where its effect can be taken into account in the elevator trim loop. After opening, the SPBK, which has been tightly closed, now has a minimum closure angle of 15°.

### **h = 125,000 feet**

Yaw jet minimum on time is increased from 80 to 320 milliseconds. This is to ensure complete burning of propellants between fire commands.

### **Mach = 5**

The rudder becomes active. The rudder is now able to offload the aileron trim, allowing ailerons to be used more for vehicle control.

### **Mach = 4**

GALR begins to ramp down to blend the transition of early entry bank into late entry. At approximately Mach 3.8 GALR will equal 1.0, which momentarily provides no roll command via the 1-GALR function. Below Mach 3.8, GALR is ramping down toward 0, which provides positive aileron commanding for the remainder of the entry, transitioning aileron commands from  $\beta$  damping during bank maneuvers to a more conventional body axis roll command.

### **Mach = 3.2**

The SPBK closes to approximately 65 percent to increase rudder effectiveness.

### **Mach = 3.0**

The elevon trim schedule may ramp up to prevent high hinge moments.

### **Mach = 2.5**

TAEM begins (MM305).  $N_z$  command replaces alpha command in the auto pitch loop. The pitch error needle now displays  $N_z$  error on the ADI. The maximum auto pitch rate being commanded is a function of true airspeed and is limited to the maximum guidance commanded  $N_z$  deltas of  $\pm 0.5g$ . A yaw rate term is brought in for turn compensation in pitch ( $r \tan \Phi$ ).

### **Mach = 2.0**

The RHC gain begins increasing to provide higher commanded pitch rates. This commanded pitch rate will be a maximum of  $\pm 9.2$  deg/sec upon reaching a Mach number of 1.2.

### **Mach = 1.5**

The maximum roll rate command begins increasing and will achieve a value of  $\pm 27$  deg/sec in CSS R/Y and  $\pm 20$  deg/sec in AUTO R/Y by Mach 0.6. The  $N_y$  feedback into the roll channel begins to decrease and reaches zero at Mach 0.9.

### **Mach = 1.25**

When flying CSS R/Y, the aileron trim integrator ceases its trim function and holds the last value of aileron trim. Crew awareness of this is important if there is constant RHC displacement in roll later in the trajectory, indicating an out-of-trim condition.

### **Mach = 1.0**

The yaw jets terminate.

In passing from supersonic to subsonic flight, the crew needs to pay particular attention to the alpha limits.

Note: If the vehicle is allowed to pitch up to higher than the upper angle-of-attack limit, a loss of vehicle control can occur. In the automatic mode, the vehicle may, when following guidance under certain off-nominal circumstances such as when air data is not incorporated, pitch up past the alpha limit and lose control.

All three control axes are  $\bar{q}$ -limited to a minimum value of 90 psf. This is to prevent any system being reactivated, such as jets turned back on, if the  $\bar{q}$  becomes low enough. An example would be during rollout when  $\bar{q}$  is rapidly decreasing.

### **Mach < 1.0**

Pitch and R/Y CSS control normally taken by the commander.

### **Mach = 0.95**

The SPBK is now being commanded by TAEM guidance for total energy modulation.

### **Mach = 0.6**

The  $P_{COR}$  is now being used in the yaw channel as a yaw rate error to generate rudder commands. This essentially provides turn coordination through landing.

### **h = 14,000 ft**

SPBK energy modulation function is beginning to be replaced by  $\bar{q}$  only modulation.

### **h < 10,000 ft**

At the approach and landing interface, guidance commands the BF to the trail position, 0° (34%), if in the BF AUTO mode.

### **h = 9000 ft**

SPBK function is working solely to control  $\bar{q}$  to 305 psf (300 KEAS).

**h = 3000 ft**

The SPBK closes to a calculated value based on wind, weight, density altitude, velocity error, aimpoint, and SPBK option.

**h = 2000 ft**

Preflare is commanded.

**h = 500 ft**

The SPBK can make an adjustment based on density altitude and wind velocity.

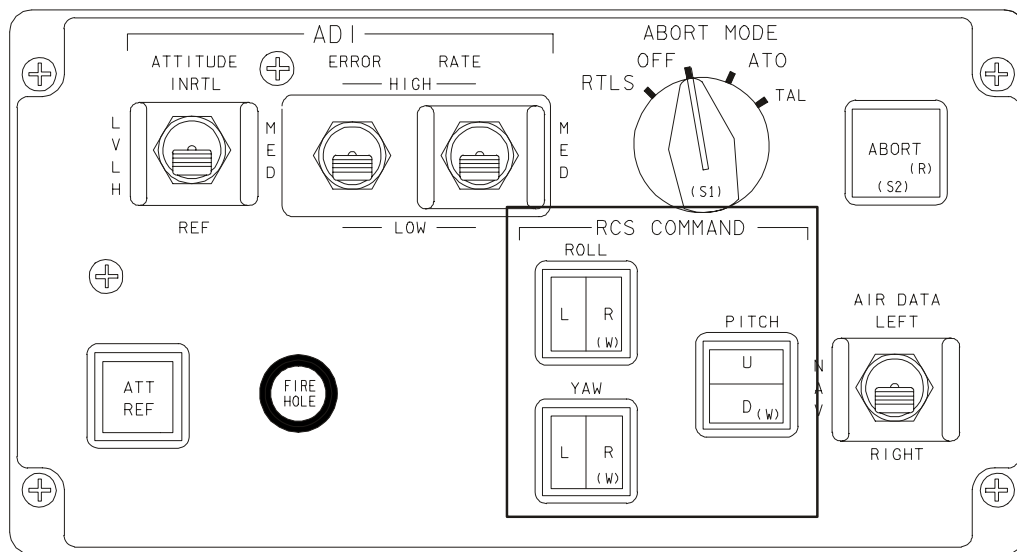
**Main gear touchdown**

Auto load balance begins. The  $N_y$  feedback loop and the rudder trim integrator loop are opened. SPBK goes full open. Flatturn flag is set.

**Nose gear touchdown**

The aileron trim loop is opened, and the load balance signal is faded. The elevator feedback loop is opened, and the elevators are commanded down in AUTO (will mode to AUTO if in CSS) to relieve the main tire load. Pitch can be moded back to CSS by the “hot stick” method or by pushing the CSS pitch pbi.

The turn coordination loop is grounded and NWS is enabled.



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**Figure 8-1. F6 Panel RCS activity lights**

**Table 8-1. RCS activity light summary**

Event	Roll	Pitch	Yaw
EI-5	Left or right light indicates jet has been commanded to fire	Up or down light indicates jet has been commanded to fire	Left or right light indicates that two jets have been commanded to fire
$\bar{q} = 10$ psf	↓ (Roll jets deact.)	↓	↓
$\bar{q} = 40$ psf	No use	↓ (Pitch jets deact.)	↓
$\bar{q} = 50$ psf	Both lights simo indicate $\geq 3$ yaw jets commanded to fire	Both lights simo indicate elevon rate saturation: ( $\pm 20$ deg/sec, 2(3) APU $\pm 14$ deg/sec, 1 APU)	↓
Mach = 1.0	No use	↓	↓ (Yaw jets deact.)
NGTD	No use	↓	No use

Note: From  $\bar{q} = 40$  to 50, four yaw jets are available for firing, while the yaw light activates for two commanded. Only at  $\bar{q} \geq 50$  does the crew have insight into > two yaw jets commanded.

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## QUESTIONS

1. When is the aerojet DAP initialized?
2. When do the RCS activity lights reconfigure?
3. When are the roll, pitch, and yaw jets deactivated?

## 9.0 ENTRY CUE CARDS

### 9.1 OBJECTIVES

At the end of this section, the student will be able to do the following:

- a. Interpret the ENTRY MANEUVERS and the ENTRY ALPHA cue cards.
- b. Identify the ENTRY CONTROL cue card.

### 9.2 ENTRY CUE CARDS

An example of an ENTRY MANEUVERS cue card is shown in Figure 9-1. Entry DAP actions and monitoring tasks are included at the appropriate event on the card. At Entry Interface minus 5 minutes, EI-5, Entry DAP is initialized with the GNC, OPS 304 PRO action by the crew. At Closed Loop Guidance initiation,  $\bar{q} \sim 8$  or Drag (D)  $\sim 3$ , begin aileron trim monitoring as the ailerons will start to trim out in response to aerodynamic forces. At Mach 10,  $V = 10K$ , the SPBK will open to 81 percent. At Mach 5,  $V = 5K$ , the crew should monitor aileron and rudder trim as the rudder becomes active. Once subsonic, the crew will take CSS control to guide the vehicle around the heading alignment cone and landing. The crew should monitor SPBK position throughout the approach and landing. After nose gear touchdown, the crew will back up the groundspeed enable flag in the software by moving the SRB SEP switch to the MAN/AUTO position and depressing the SEP pushbutton. The crew should check that Load Relief is set by checking that the elevons are approximately  $10^\circ$  down and noting the Pitch axis is now in AUTO.

An ENTRY ALPHA cue card is shown in Figure 9-2. For the different velocities ( $VR$ ), the expected angle of attack ( $\alpha$ ) is shown. Also shown for easy reference are the range (R), altitude (H), and reference bank angle ( $R_{ref}$ ). The angle of attack shown is the design flight profile. At the high Mach numbers (velocities), the alpha has a  $\pm 3^\circ$  allowable band. The high Mach numbers show a constant alpha during the temperature control phase and the equilibrium glide phase. Shortly after going to the constant drag phase, the alpha begins to decrease while maintaining a constant drag acceleration. The alpha continues to come down during the transition phase from high angles of attack to low.

From TAEM, at Mach 2.5, the angle of attack continues to decrease to a final value of  $7^\circ$  as the vehicle begins to go subsonic. In the center of the card is a table that gives the alpha to be flown for maximum L/D ratio for several Mach numbers.

**ENTRY MANEUVERS**

FLIGHT CONDITIONS	MANEUVER
EI-5	✓LVLH ATT GNC, OPS 304 PRO * If PREBANK, R/Y – CSS * * Roll at 1°/sec to <input type="text"/> <input type="text"/> <input type="text"/> * * Maintain PREBANK ± 5° * If previous OMS OX TK or He TK or RCS OX TK leak: <input type="text"/> VENT DOORS – OP PTI – ENA at EI-5 when applicable
$\bar{q} = 1$	(AOA) HYD MN PUMP PRESS (three) – NORM
'Guidance Box' @ $\bar{q} \sim 8$ or $D \sim 3$	CLOSED LOOP GUIDANCE _____:_____: * If PREBANK: P,R/Y – AUTO * Begin AIL trim monitoring
D = 11	✓DRAG H (FORCE if editing)
V = 19K	✓MPS/TVC ISOL VLV – CL
V = 15K	✓NAVAIDS (I/O RESET if reqd) * If ELS: UHF MODE – G T/R *
V = 12K	RAD BYP VLV MODE (two) – AUTO CNTLR LOOP (two) – AUTO B(A)
V = 10K	✓SPDBK to 81%
$\Delta Az = 10.5^\circ$	FIRST ROLL REVERSAL <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/>

ENT-6a/E/L

FLIGHT CONDITIONS	MANEUVER
V = 7K	✓TACAN status
V = 5K	ADTA PROBES – DEPLOY (✓HEAT) Begin AIL and RUD trim monitoring
M = 2.7	✓APUs HUD PWR (two) – ON * If M < 2.5; P CSS for ADTA to G&C incorp *
M = 2.0	Ensure ADTA to G&C else ✓Theta limits
M < 1.0	✓R FLT CNTLR – ON P, R/Y – CSS as reqd ✓SPDBK CMD vs POS ✓NWS – 1 Lock Inertia Reels MAX Nz <input type="text"/> <input type="text"/> <input type="text"/>
M = 0.7	✓LG EXTEND ISOL VLV – OP
h = 15K	✓MLS
h = 10K	✓A/L, TABS/VISORS – CL/LES O2 – ON (KSC)
h = 2K	LANDING GEAR ARM pb – ARM
h = 300	LANDING GEAR DN pb – DN
MAIN GEAR TD	✓SPDBK – 100%
V = 195 KEAS	DRAG CHUTE pb (two) – ARM, DPY (simo)
V = 185 KEAS	DEROTATE
NOSE GEAR TD	SRB SEP – MAN/AUTO and depress pb ✓Auto Load Relief ✓HYD BRAKE ISOL VLV (three) – OP
MIDFIELD and V < 140 KGS	BRAKE as required (8–10 fps <sup>2</sup> , –0.25 to –0.3G)
* If 5K' remaining and V > 140 KGS – MAX BRAKING *	
V = 60 KGS	DRAG CHUTE JETT pb – JETT
V = 40 KGS	BRAKE < 6 fps <sup>2</sup> (–0.2G) (Antiskid cutout)
WHEEL STOP	Go to ENT C/L, <u>POST LANDING PROCEDURES</u>

ENT-6b/E/R  
(Partial)

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**Figure 9-1. ENTRY MANEUVERS cue card**

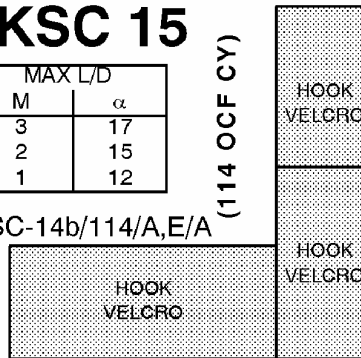
**ENTRY ALPHA**

VR	$\alpha_{ref}$	R	H	H <sub>ref</sub>	Rref
25	40	4402	400		
24	HI 40 LO	2615	247	-46	L79
23	43 40 37	2151	239	-63	69
22	43 40 37	1796	232	-83	62
21	43 40 37	1516	225	-105	59
20	43 40 37	1293	218	-123	58
19	43 40 37	1117	211	-145	59
18	43 40 37	972	204	-170	61
17	43 40 37	857	197	-189	62
16	43 40 37	764	190	-202	63

**KSC 15**

MAX L/D	
M	$\alpha$
3	17
2	15
1	12

ASC-14b/114/A,E/A



15	43 40 37	686	184	-118	63
14	43 40 37	615	180	-126	R60
13	43 40 37	548	180	-136	56
12	43 40 37	485	174	-151	55
11	43 40 37	428	168	-193	54
10	41 38 35	375	162	-173	50
9	39 36 33	323	156	-208	47
8	37 34 31	273	148	-242	43
7	33 30 27	228	140	-267	L39
6	30 27 24	185	129	-271	38
5	26 23 20	143	115	-271	40
4	22 19 18	105	101	-264	41
3	19 16 15	75	89	-248	R39
2.5	15	61	81	-261	
2	11	49	74	-283	
1.5	9	38	63	-329	
1	8	28	50	-265	

Figure 9-2. ENTRY ALPHA cue card

The ENTRY CONTROL cue card is shown in Figure 9-3. This cue card contains procedures for off-nominal situations. These include low aft RCS propellant quantities, which require the crew to select No Yaw Jet with the Entry Mode switch. Also included are procedures for saturated, or maximum, aileron trim and a procedure to deal with orbiter or flight control system oscillations or RCS jet command cycling leading to excessive propellant usage. The details of these procedures are covered in other materials such as the Entry Flight Procedures Handbook and the Entry DAP Skills Briefing 21001.

### ENTRY CONTROL

#### ARCS QTY (L + R) < 10%

ARCS QTY = 0 & JETS FAIL OFF	1. ENTRY MODE – NO Y JET (R/Y CSS; expect sluggish control)
$\bar{q} \geq 20$ & $M > 6$	2. [G51] ELEVON FIXED – ITEM 18 EXEC (*)
CONTROL PROBLEMS* & ARCS QTY > 0	3. ENTRY MODE – AUTO When control regained: 4. ENTRY MODE – NO Y JET 5. ✓AIL trim
$M < 6$ & ARCS QTY > 0	6. ENTRY MODE – AUTO
$M < 5$	7. TRIM/RHC PNL – ENA 8. TRIM ROLL – away from AIL trim (to < 1)

\*Region of least margin: M 12–8

#### AIL TRIM $\geq 3^\circ$

TAL	1. [G51] WRAP MODE – ITEM 45 EXEC (ACT)														
AIL trim = 5	2. BF – MAN 3. BF – UP (to 0%)														
NO Y JET	4. Perform roll reversals at 3°/s (expect sluggish control)														
$M < 13$ & AIL trim = 5	5. P – CSS 6. Fly $\alpha$ per schedule: <table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td>M</td> <td>12</td> <td>11</td> <td>10</td> <td>9</td> <td>8-6</td> <td>5</td> </tr> <tr> <td><math>\alpha</math></td> <td>37</td> <td>36</td> <td>35</td> <td>33</td> <td>30</td> <td>26</td> </tr> </table>	M	12	11	10	9	8-6	5	$\alpha$	37	36	35	33	30	26
M	12	11	10	9	8-6	5									
$\alpha$	37	36	35	33	30	26									
$M < 5$	7. TRIM/RHC PNL – ENA 8. TRIM ROLL – away from AIL trim (to < 1) 9. P – AUTO														
$M < 2$	10. BF – AUTO														

ENT–10a/A,E/A

#### HIGH-FREQ OSC OR SURF/JET CYCLE

Returning PL > 10K lbs	1. [G51] ✓FILTER ALT – ITEM 21 (*)
	2. P, R/Y – CSS
Osc/Cycle continues	3. ENTRY MODE – LO GAIN
Osc/Cycle stops	4. ENTRY MODE – AUTO 5. P, R/Y – AUTO

ENT–10b/A,E/A

Figure 9-3. ENTRY CONTROL cue card

## QUESTIONS

1. Using Figure 9-1, at what point does the crew take CSS to begin manually flying the orbiter?
  
2. Using Figure 9-2, find the following for Mach 17:
  - (a) Reference alpha
  - (b) Range
  - (c) Altitude
  - (d) Vertical velocity ( $\square$ )
  - (e) Bank angle

## 10.0 FLIGHT CONTROL SYSTEM MONITORING

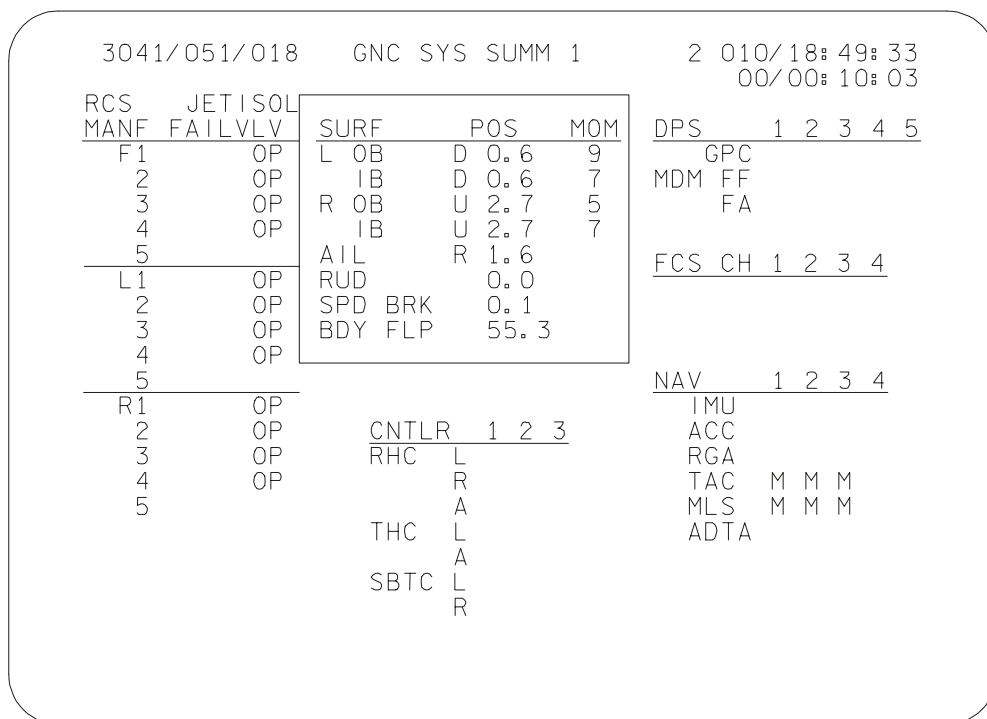
### 10.1 OBJECTIVES

At the end of this section, the student will be able to state the aerojet software conditions on PASS GNC SPEC 51, OVERRIDE.

### 10.2 CREW DISPLAYS

Figures 10-1 through 10-4 show displays used for FCS monitoring.

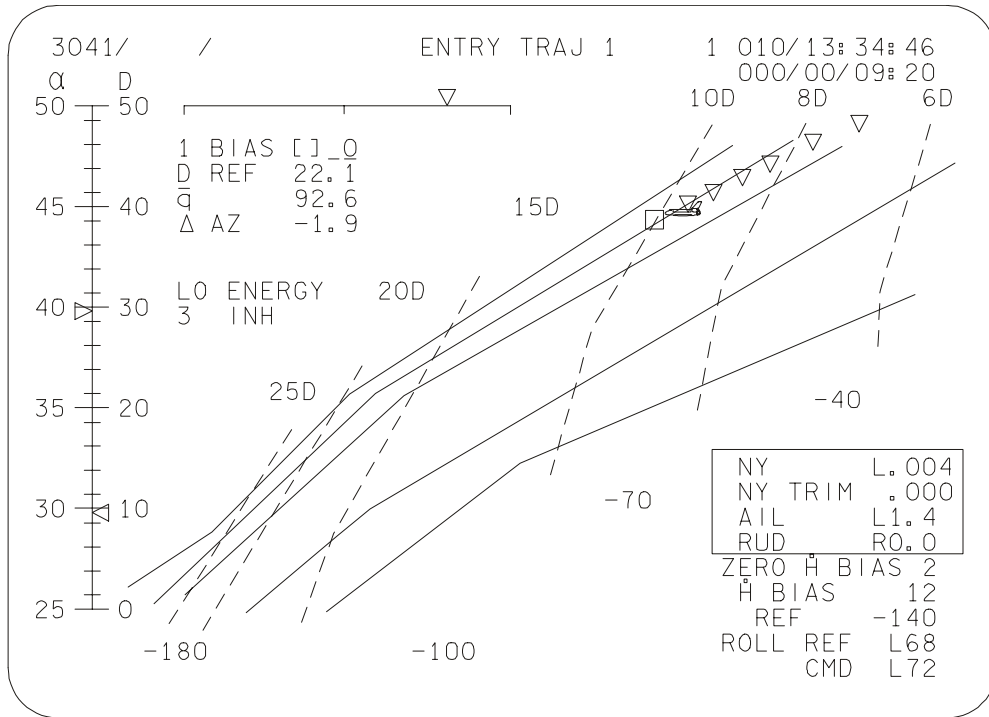
GNC SYS SUMM 1 provides aerosurface position and elevon hinge moment data, as well as FCS channel status.



006497025. CRT: 1

**Figure 10-1. GNC SYS SUMM 1**

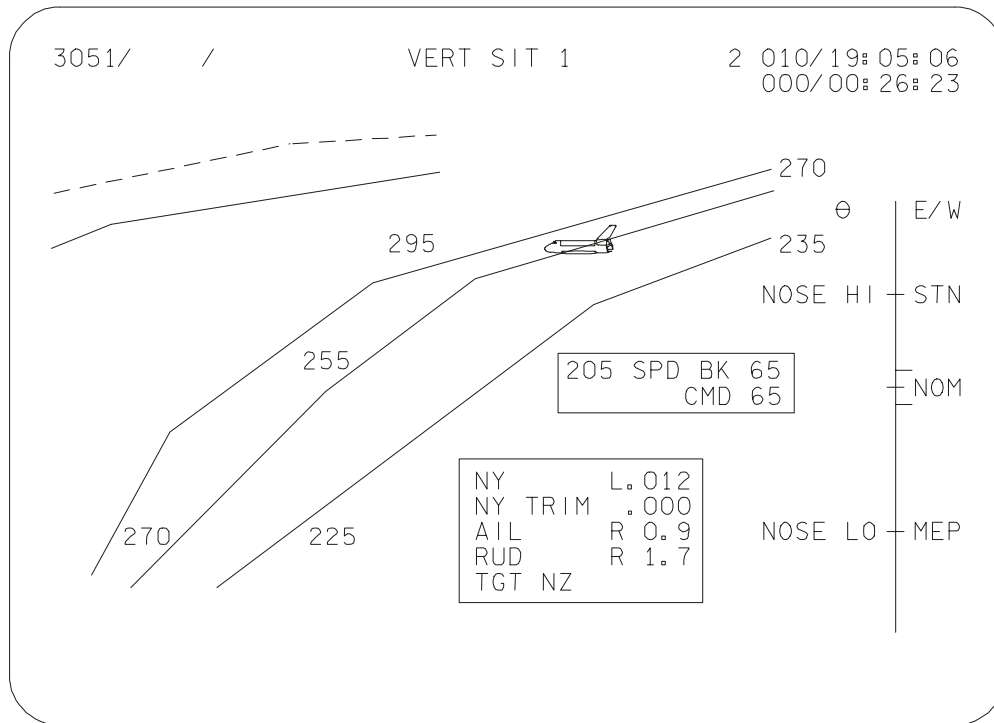
Entry Traj 1 – 5 displays show steady state lateral acceleration (NY), lateral trim (NY TRIM), aileron trim (AIL), and rudder trim (RUD).



006497026. CRT; 1

**Figure 10-2. ENTRY TRAJ**

Once in TAEM, the VERT SIT shows the trim data, as well as SPBK position and CMD.

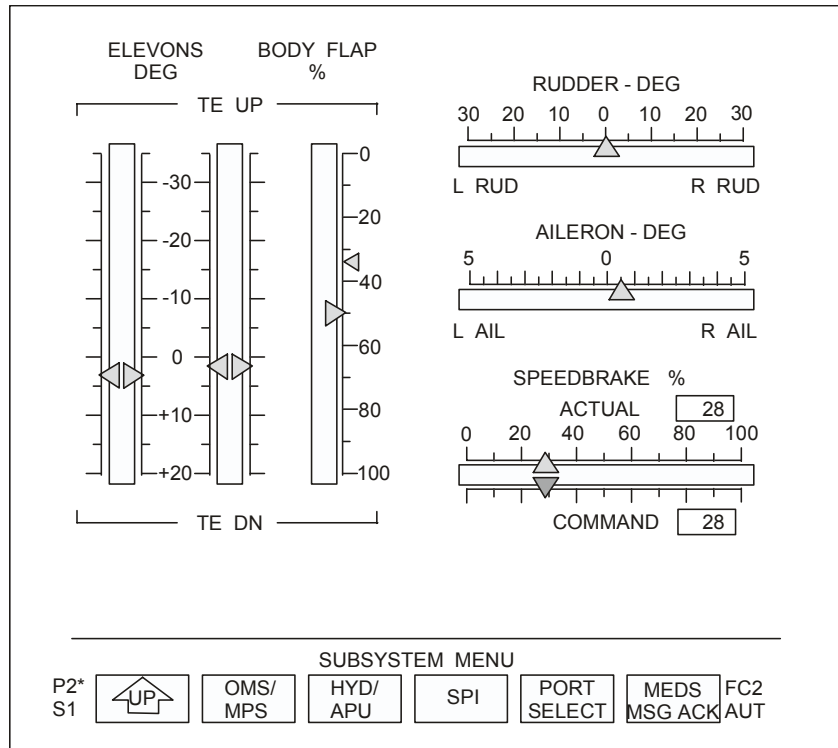


006497024. CRT; 1

**Figure 10-3. VERT SIT**



The SPI, Figure 10-4, displays the position of each of the aerosurfaces. The aileron display is calculated as the average difference between the left and right elevon panels. As previously mentioned, the SPI displays the combined control and trim commands to the aerosurfaces. For actual trim values, you should look at the Entry Traj or Vert Sit displays.



**Figure 10-4. SPI**

Through the use of SPEC 51, OVERRIDE, the crew can check or alter, by keyboard inputs, software conditions of the entry DAP. The first, shown in Figure 10-5, is the software position of the Entry Mode switch. As can be seen in the figure, the Entry Mode switch (ROLL MODE on the display) is indicating AUTO. Moving the switch itself, first to the Low Gain (L GAIN) position, then to the No Yaw Jet (NO Y JET) position changes the displays, as shown in Figures 10-6 and 10-7.

```

3041/051/          OVERRIDE          1 007/21:51:01
                                         000/00:19:55

ABORT MODE
TAL      1
ATO      2
ABORT    3
THROT MAX 4
          ABT 50
          NOM 51
PRPLT DUMP
ENA INCNT 5
OMS DUMP
ARM      6
START   7
STOP    8
9 QUAN/SIDE .84
OMS DUMP TTG 459

AFT RCS 13
14 TIME  0

FWD RCS 15
16 TIME  0

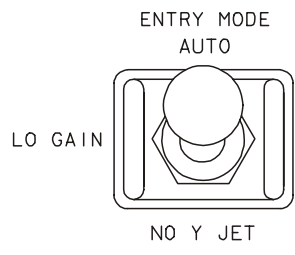
ELEVON   FILTER  ATMOSPHERE
AUTO 17*  NOM 20*  NOM 22*
FIXED 18  ALT 21  N POLE 23
SSME REPOS 19 ENA 6 POLE 24

IMU STAT ATT DES          PRL
1      1  25          SYS AUT DES
2      26          1 28* 31
3      27          2 29* 32
          30* 33

ADTA      H      a      M      DES
L 1      0  0.0  0.00 34
3      0  0.0  0.00 35
R 2      0  0.0  0.00 36
4      0  0.0  0.00 37

ET SEP    ROLL MODE AUTO
AUTO 38   AUTO SEL 42
SEP 39   WRAP MODE 45 ACT

ET UMB DR VENT DOOR CNTL
CLOSE 40  OPEN 43
RCS RM MANF CLOSE 44* CL
CL OVRD 41
    
```



006497001. CRT; 2

Figure 10-5. SPEC 51 OVERRIDE

```

3041/051/          OVERRIDE          1 007/21:51:01
                                         000/00:19:55

ABORT MODE
TAL      1
ATO      2
ABORT    3
THROT MAX 4
          ABT 50
          NOM 51
PRPLT DUMP
ENA INCNT 5
OMS DUMP
ARM      6
START   7
STOP    8
9 QUAN/SIDE .84
OMS DUMP TTG 459

AFT RCS 13
14 TIME  0

FWD RCS 15
16 TIME  0

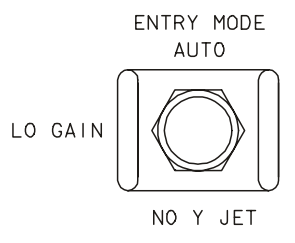
ELEVON   FILTER  ATMOSPHERE
AUTO 17*  NOM 20*  NOM 22*
FIXED 18  ALT 21  N POLE 23
SSME REPOS 19 ENA 6 POLE 24

IMU STAT ATT DES          PRL
1      1  25          SYS AUT DES
2      26          1 28* 31
3      27          2 29* 32
          30* 33

ADTA      H      a      M      DES
L 1      0  0.0  0.00 34
3      0  0.0  0.00 35
R 2      0  0.0  0.00 36
4      0  0.0  0.00 37

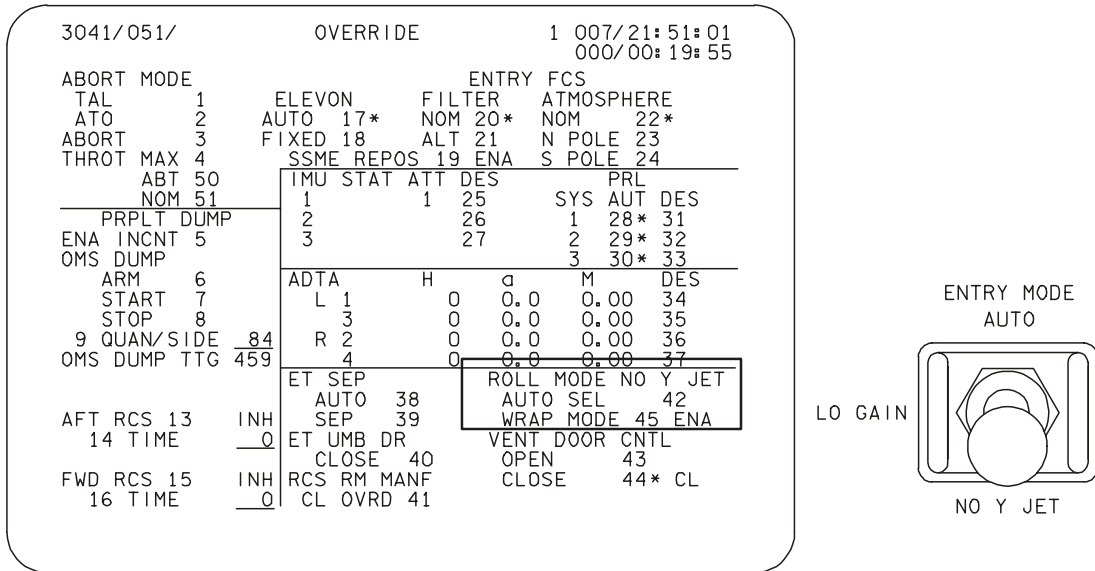
ET SEP    ROLL MODE LGAIN
AUTO 38   AUTO SEL 42
SEP 39   WRAP MODE 45 ACT

ET UMB DR VENT DOOR CNTL
CLOSE 40  OPEN 43
RCS RM MANF CLOSE 44* CL
CL OVRD 41
    
```



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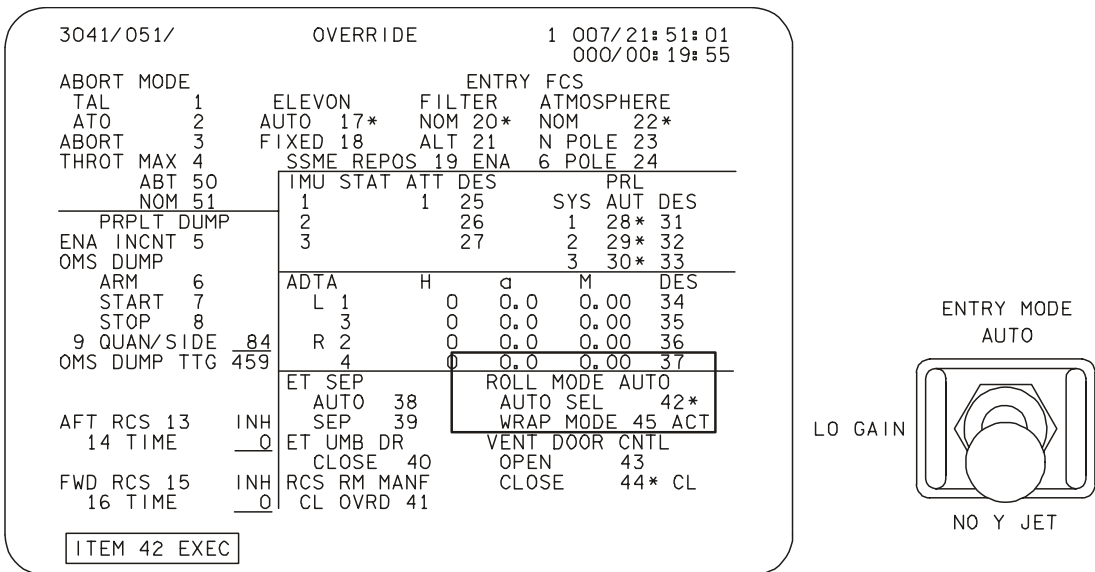
Figure 10-6. SPEC 51 OVERRIDE, LO GAIN



006497003. CRT; 2

**Figure 10-7. SPEC 51 OVERRIDE, NO Y JET**

With a keyboard input, the software selection of the switch function can be changed to AUTO, regardless of the actual switch position. In other words, with the switch physically in NO Y JET, the logic can be made to be in the AUTO position by executing an item 42, AUTO SEL. The display will be as shown in Figure 10-8. The entry DAP functions normally with the normal gains, while the switch resides in NO Y JET. With the switch still in NO Y JET, executing item 42 again puts the software back in agreement with the switch position, as in Figure 10-7.



006497004. CRT; 2

**Figure 10-8. SPEC 51 OVERRIDE, ITEM 42 EXEC**

Another software condition of the Entry DAP available on SPEC 51 is to enable or disable the Wraparound DAP. Item 45 on both PASS and BFS allows the crew to enable or disable Wrap DAP. On a typical EOM entry, Wrap DAP is initialized enabled and becomes active at  $\bar{q} = 10$ . The display will show Enable (ENA), then Active (ACT). With an Item 45 Exec, the crew may Inhibit (INH) Wrap DAP.

SPEC 51 also provides the crew with the information concerning the selection of the elevon schedule and the body bending filter. In the upper center portion of the display, items 17 and 18 represent the AUTO and FIXED elevon schedules, respectively, while items 20 and 21 are the Nominal (NOM) and Alternate (ALT) body-bending filters, with an asterisk beside the elevon schedule and filter currently selected. During a normal entry (going from OPS 2 to OPS 3), the entry DAP would come up initialized in the AUTO configuration for the elevon and the appropriate body bending filter selected.

Some off-nominal situations require the crew to select either the Fixed elevon schedule or the other body bending filter. The body-bending filter may change for an AOA or unplanned payload return (no deploy) case. A heavy payload being returned or a payload with flexibility that would interact with the orbiter structure in such a way as to set up vibration in the structure of the orbiter, that the RGAs may detect as rotational rates, requires a change in the body-bending filters. The Entry Checklist procedures provide direction on which ELEVON and FILTER item entry are required.

The BFS SPEC 51 is shown in Figure 10-9. Note that there is no software selection to AUTO in the BFS.

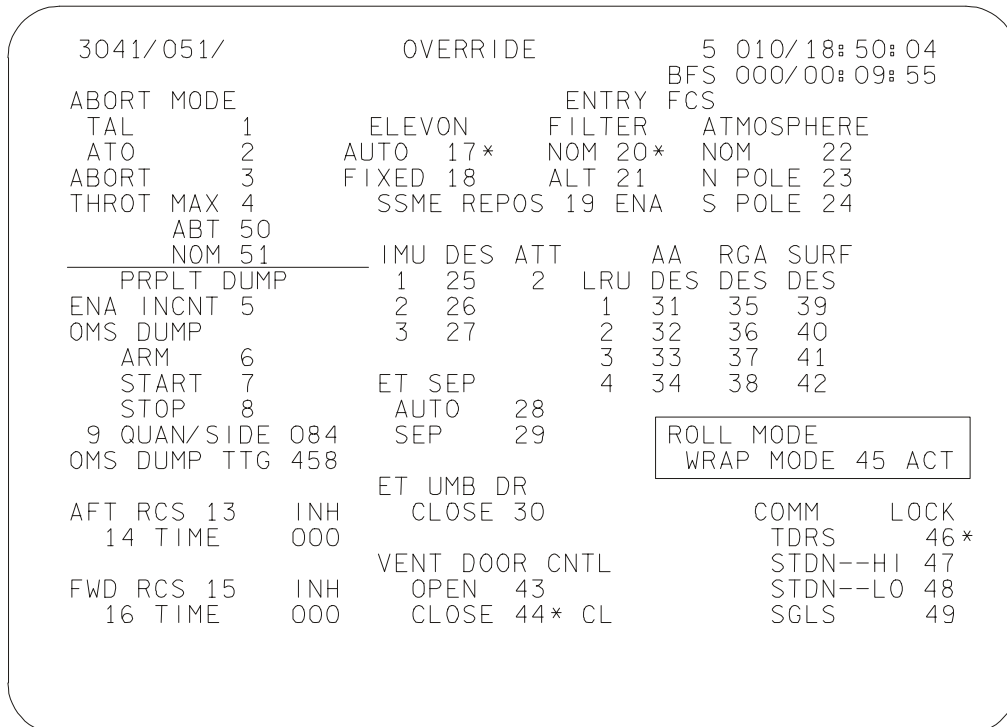


Figure 10-9. SPEC 51 OVERRIDE (BFS)

## QUESTIONS

1. State the three entry DAP software conditions that can be seen on PASS GNC SPEC 51, OVERRIDE.
2. State how to change the software status of the Entry mode switch back to AUTO if the switch is physically stuck in NO Y JET or LO GAIN.

## **11.0 AUTOMATIC PROGRAM TEST INPUTS**

### **11.1 OBJECTIVES**

At the end of this section, the student will be able to state the purpose of PTIs.

### **11.2 AUTOMATIC PTI**

The purpose of the PTIs is to provide automatic test maneuvers during flight to obtain flight data from which aerodynamic coefficients can be extracted postflight. The data are used to define the aerodynamic characteristics of the vehicle, allow expansion of the operational envelope, and reduce aero database uncertainty.

PTIs are executed automatically by the entry DAP and are input into the control system downstream of the gains and filters so that a known control deflection (for example, a 5° aileron sweep) or jet firing can be made (refer to Figures 2-5, 4-6, and 5-6). Being automatic, they can be more precise and reduce the crew workload.

Certain flight constraints must have been met for 4 seconds for a maneuver to be executed. These constraints include restrictions on body rates, altitude acceleration, and heading to ensure that the vehicle is in the proper condition (stabilized attitude) before PTI initiation. It should be noted that the vehicle control has to be in AUTO in all axes for automatic PTIs to be accomplished.

The maneuvers are restricted to certain regions of the entry trajectory (“windows”) and are cued by Mach number or  $\bar{q}$ . When the vehicle is inside a maneuver window but the constraints have not been met, “PTI” begins flashing on the SPEC 50 display. The PTI becomes static when the maneuver is executed and disappears when out of the window, whether the maneuver is or is not executed.

The PTI logic, which has been I-loaded before flight, generates the signals sent to the DAP when the maneuver criteria have been met. These signals usually form doublets (example, left rudder input, followed by right rudder input, then back to neutral), which are superimposed on the normal commands. The axes affected and the controls used in each maneuver are decided preflight, and a series of pulses can be executed in one maneuver.

Because the idea of the maneuver is to obtain controlled input and response for flight data extraction, it becomes obvious that all other control inputs should be minimized; therefore, the commanded roll rate is zero, the aileron and rudder trim integrator inputs are zero, and the pitch jet input for elevator trim is zero.

A PTI can be terminated or inhibited at any time in one of three ways. An item 1 on SPEC 50 PTI Inhibit (INH)/Enable (ENA) indicator will inhibit execution of a PTI, as well as going to CSS in either axis by means of the pbi or “hot stick downmode” with the RHC. When any maneuver is inhibited, it or any of the succeeding PTIs will have to be enabled by returning the control to AUTO in all axes and executing item 1 on SPEC 50 to ENA (see Figure 11-1).

a. PTI logic

The following constraints must be met for  $\approx 4$  sec:

1. Body rates  $p < 1.5$ ,  $q < 0.5$ ,  $r < 0.5$  (deg/sec)
2. Altitude acceleration  $\ddot{h} < 4$  ft/sec<sup>2</sup>
3. Not outside heading error limits (inhibit PTI if near a roll reversal)
4. Roll reversal not started in last 42 sec
5. ADTA providing air data to DAP if Mach  $< 2.5$
6. Pitch and roll/yaw in AUTO mode
7. Crew sets enable flag

b. Maneuver selection

1. PTIs are executed only inside certain trajectory windows
2. Cued by Mach or dynamic pressure
3. Average of 8 to 10 maneuvers during early flights of the shuttle program

c. Crew displays

1. If trajectory is inside PTI window but constraints are not met, “PTI” flashes
2. When maneuver is executed, PTI becomes static

d. Maneuver execution

When maneuver criteria have been met, the PTI logic generates signals that are sent to DAP

1. Signals are usually in the form of doublets, which are integrated
2. These signals are superimposed on normal commands

3. Controls effectors are  $\delta_e$ ,  $\delta_r$ ,  $\delta_a$ , roll-pitch-yaw jets
4. Series of pulses can be executed in a single maneuver

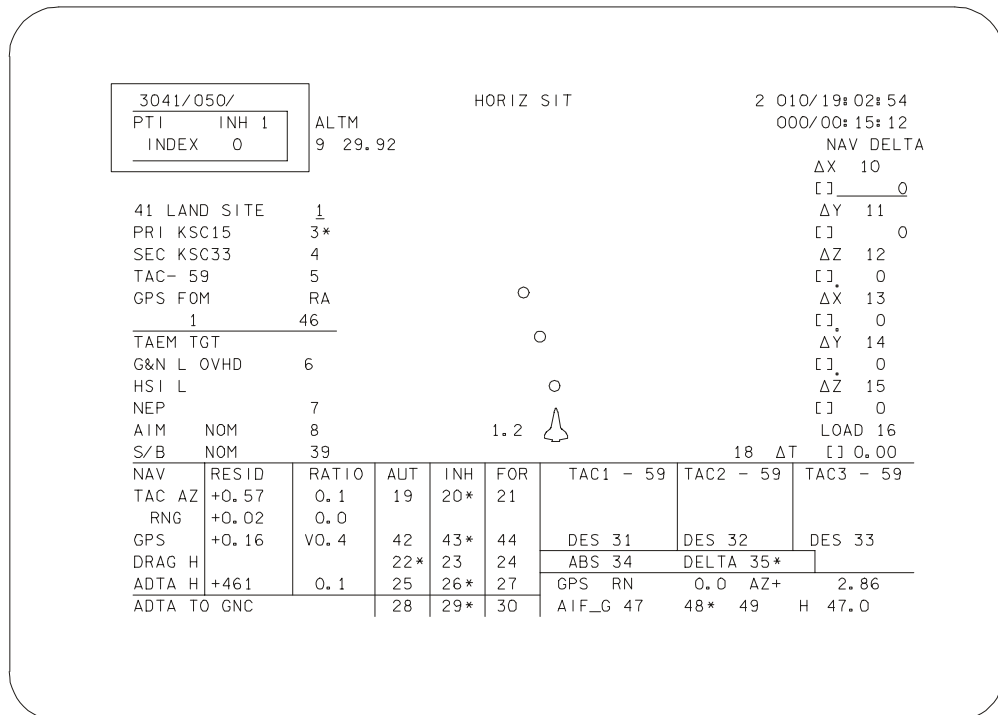
While pulse is being executed

1. Commanded roll rate is set = 0
2.  $\delta_a$ ,  $\delta_r$  trim integrator inputs = 0
3. G JET is grounded (pitch jet to elevator crossfeed)

Maneuver can be terminated at once by:

1. Keyboard (item 1 on SPEC 50)
2. Pushing either pitch or roll/yaw CSS pbi
3. Pushing control stick, "hot stick downmode"

Note: To re-enable PTIs, return to AUTO, and execute item 1 on SPEC 50.



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Figure 11-1. SPEC 50 PTI interface



## QUESTIONS

1. State the purpose of PTIs.

## 12.0 GRTLS DIFFERENCES

### 12.1 OBJECTIVES

At the end of this section, the student will be able to state the reason for differences between the nominal OPS3 entry DAP and GRTLS DAP.

### 12.2 INTRODUCTION

The differences between the nominal EOM entry DAP and the GRTLS DAP are listed below. A significant number of the differences are gain reductions in GRTLS as compared to the normal entry. These gain reductions are made to account for the heavier return weight, different angle of attack versus Mach number profiles, and higher anticipated dynamic pressures. In the pitch axis, the elevators are active for control immediately, and turn compensation is available at the extended TAEM interface ( $r \tan \Phi$  at Mach 3.2). Also, the SPBK schedule is wholly contained in guidance during GRTLS. In GRTLS, the body flap follows a guidance-computed algorithm to assist in pitch trim.

#### **Pitch axis**

- a. Gain reduction on GTRE – Gain scheduling elevator trim rate
- b. Gain reduction on GTAS – Gain as a function of true airspeed
- c.  $N_z$  acceleration errors smoothed and filtered for the pitch rate command
- d. Increased angle of attack error limit before generating effector commands
- e. Elevons active for control immediately
- f.  $r \tan \Phi$  not active during:  $\alpha$  recovery,  $N_z$  hold,  $\alpha$  transition (i.e., before TAEM)
- g. Gain reduction on GQAL – Gain converting auto  $\alpha$  CMD to pitch rate error
- h. Body-bending filter coefficients applicable for payload return

**Yaw axis** - Wraparound DAP not available

**Roll axis** - Gain reduction GDA - Gain used to convert roll rate error to preliminary aileron command, gain also made a function of angle attack

**SPBK** - Commands scheduled in TAEM guidance

**Body flap** - Elevon trim scheduled for heavyweight, payload return

## QUESTIONS

1. Why are there differences between nominal entry DAP and GRTLS DAP?

### **13.0 REFERENCES**

1. STS 83-0007-29, Space Shuttle Orbiter Operational Level C Functional Subsystem Software Requirements, Guidance, Navigation, and Control, Part C – Flight Control: Entry – GRTLS; Boeing Reusable Space Systems, November 24, 1999.
2. JSC-19350-112, NSTS Flight Software Initialization Load, Volume II: Flight Specific Requirements STS-112 Base Patch Cycle; June 6, 2002
3. JSC-11542, Rev. D, Flight Procedures Handbook, Entry; July 1, 1995.

**APPENDIX A      ACRONYMS AND ABBREVIATIONS**

A/L	Approach and Landing
AA	Accelerometer Assembly
ACT	Active
ADI	Attitude Director Indicator
ADTA	Air Data Transducer Assembly
AGL	Above Ground Level
ALT	Alternate
AOA	Abort Once Around
APU	Auxiliary Power Unit
AUTO	Automatic Control Mode
	Automatic Guidance
AUTO P	Pitch Axis in Automatic mode
AUTO R/Y	Roll/Yaw Axes in Automatic mode
BF	Body Flap
BFS	Backup Flight System
CDR	Commander, Space Shuttle flight crew
c.g.	center of gravity
CSS	Control Stick Steering
CSS P	Pitch Axis in Control Stick Steering mode
CSS R/Y	Roll/Yaw Axes in Control Stick Steering mode
D	Drag
DAP	Digital Autopilot
DDU	Display Driver Unit
DRPRM	compensated yaw rate feedback term in yaw channel
EI	Entry Interface
ELS	Emergency Landing Site
ENA	Enable
EOM	End of Mission
ET SEP	External Tank Separation (switch)
FCS	Flight Control System
FLATTURN	Landing/Rollout Discrete
GALR	Gain for Ailerons in Roll Channel
GDA	Gain for roll rate error
GNC	Guidance, Navigation, and Control
GPC	General Purpose Computer
GQAL	Gain for pitch rate versus angle of attack error
GRTL5	Glide Return to Launch Site
GSENB	Ground Speed Enable

HAC	Heading Alignment Cone
HUD	Heads Up Display
IMU	Inertial Measurement Unit
INH	Inhibit
JSC	Lyndon B. Johnson Space Center
JSL	Jet Select Logic
KEAS	Knots Equivalent Airspeed
L/D	Lift to Drag
L GAIN	Low Gain
MAN	Manual
MEDS	Multifunction Electronic Display System
MGTD	Main Gear Touchdown
MM	Major Mode
MOD	Mission Operations Directorate
NGTD	Nose Gear Touchdown
NOM	Nominal
NO YJET	No Yaw Jet
NWS	Nosewheel Steering
OPS	Operations Sequence (keyboard entry)
PASS	Primary Avionics Software System
pbi	pushbutton indicator
$P_{COR}$	Compensated roll rate feedback term in roll channel
PLT	Pilot, Space Shuttle flight crew
PRL	Priority Rate Limiting
PRO	Proceed (keyboard entry)
psf	pounds per square foot
PTI	Programmed Test Input
R/Y	Roll/Yaw
RCS	Reaction Control System
RGA	Rate Gyro Assembly
RHC	Rotational Hand Controller
RM	Redundancy Management
ROLLOUT	Rollout Discrete
RPTA	Rudder Pedal Transducer Assembly
RTLS	Return to Launch Site
SBTC	Speedbrake Thrust Controller
SOP	Software Operating Program
SPBK	Speedbrake

SPI	Surface Position Indicator
SRB SEP	Solid Rocket Booster Separation (switch)
TAEM	Terminal Area Energy Management
TAL	Transoceanic Abort Landing
TAS	True Airspeed
USA	United Space Alliance
WONG	Weight on Nose Gear
WOW	Weight on Wheels
WOWLON	Weight on Wheels Latched On
Wrap DAP	Wraparound Digital Automatic Pilot

**APPENDIX B    SYMBOLS**

$A_y$	Scaled lateral acceleration, g
$b$	Wingspan, ft
$C_A$	Axial force coefficient
$C_\ell$	Rolling moment coefficient
$C_\ell_\beta$	Rolling moment coefficient due to sideslip angle
$C_\ell_{\delta_a}$	Rolling moment coefficient due to aileron
$C_{m_{SB}}$	Pitching moment due to SPBK
$C_N$	Normal force coefficient
$C_n$	Yawing moment coefficient
$C_{n_\beta}$	Yawing moment coefficient due to sideslip angle
$C_{n_{\delta_a}}$	Yawing moment coefficient due to aileron
$g$	Acceleration due to gravity, $1g = 32.2 \text{ ft/sec}^2$
$H, h$	Altitude, ft
$\dot{H}$	Altitude rate, ft/sec
$L/D$	Lift to drag ratio
$M$	Mach number
$N_y$	Lateral acceleration, g
$N_z$	Normal acceleration, g
$N_{z_{cmd}}$	Commanded normal acceleration, g
$N_{z_{err}}$	Difference between commanded and feedback normal acceleration, g
$p, q, r$	Vehicle rotational rates, deg/sec (roll, pitch, yaw)
$p_b, q_b, r_b$	Vehicle body axis rotational rates, deg/sec (roll, pitch, yaw)



$p_s, q_s, r_s$	Vehicle stability axis rotational rates, deg/sec (roll, pitch, yaw)
$p_{cmd}$	Commanded roll rate, deg/sec
$p_{ss}$	Steady state roll rate, deg/sec
$\bar{q}$	Dynamic pressure, psf
$q_{cmd}$	Commanded pitch rate, deg/sec
$q_{err}$	Pitch rate error, deg/sec
$R$	Range, nautical miles
$r_{err}$	Difference between commanded and feedback yaw rates, deg/sec
$R_{ref}$	Reference bank angle, deg
$r_{ss}$	Steady state yaw rate, deg/sec
$V$	Velocity, ft/sec
$VR$	Relative velocity, ft/sec
$x, y, z$	Principal axes
$\alpha$	Angle of attack, deg
$\alpha_{cmd}$	Commanded angle of attack, deg
$\beta$	Sideslip angle, deg
$\dot{\beta}$	Rate of change of sideslip angle, deg/sec
$\Delta y$	Center of gravity offset in y axis, inches
$\delta_a$	Aileron angle, deg
$\delta_{atrim}$	Trim aileron angle, deg
$\delta_{BF}$	Body Flap angle, deg
$\delta_e$	Elevator angle, deg
$\delta_r$	Rudder angle, deg

$\delta_{SB}$	SPBK angle, deg
$\theta$	Pitch angle, deg
$\phi$	Bank angle, deg
$\phi_{cmd}$	Bank angle command, deg
$\psi$	Yaw angle, deg
$\omega$	Vehicle heading angular rate, deg/sec

## APPENDIX C ANSWERS

### SECTION 1

1. Which two control systems does the entry DAP command?

Entry DAP commands the

- a. Aerodynamic control surface system
- b. RCS

2. What are the two ways entry DAP is provided with command rates?

Entry DAP is provided with command rates

- a. By the pilot through CSS
- b. By automatic guidance

3. Which input data are necessary for determining control requirements?

Input data include

- a. Navigation-derived parameters
- b. Rate gyro and accelerometer outputs
- c. Control surface position feedback
- d. Guidance commands
- e. Past values of surface and jet commands

**SECTION 2**

1. Which three separate aerodynamic control surfaces control the pitch attitude of the shuttle?

Three control surfaces that control pitch attitude are

- a. Elevons
- b. BF
- c. SPBK

2. When are pitch jets deactivated?

Pitch jets are deactivated when  $\bar{q}$  is greater than 40 psf.

3. When are elevators active for control?

Elevators are active for control when  $\bar{q}$  becomes greater than 2 psf.

4. Describe turn compensation.

Turn compensation is the amount of pitch rate needed to keep the nose of the shuttle up during a turn.

5. Describe load relief bias.

Load relief bias assists in offloading the main landing gear during rollout. The elevators are driven down, reducing the load on main gear and tires.

6. What is the purpose of the BF?

The BF is a pitch trim device used to keep the elevons on or near a predetermined position schedule.

7. What is the difference between the AUTO and FIXED elevon schedule?

The AUTO elevon schedule is selected to place the elevons where they are most effective without exposing the BF or elevons to excessive heating or high hinge moments by biasing the elevon position based on BF position. The AUTO elevon schedule can respond effectively to a wide range of X c.g. positions. The FIXED elevon schedule does not take BF position into account and thus could drive the BF to a max up or down position, exposing the BF to excessive heating or high hinge moments. The FIXED elevon schedule can only provide optimum control for approximately 1/3 of the X c.g. range of the orbiter.

8. How can the crew manually position the BF?

By pushing the BF pbi, the crew can select manual BF and then drive the BF with the manual BF switch. "MAN" illuminates on both pbis.

9. What are the two purposes of the SPBK?

The SPBK is used to aid in

- a. Trimming the vehicle in pitch from Mach 10 to Mach 0.95
- b. Modulating energy below Mach 0.95

10. How can the crew manually position the SPBK?

The crew takes manual SPBK control by depressing the takeover pushbutton on the SBTC. They can command SPBK position by moving the SBTC forward and aft. Only one SBTC may command the SPBK at a time.

**SECTION 3**

1. Describe the stability axis system.

The stability axes differ from the body axes by the displacement of the X and Z axes following a rotation about the Y-axis through the angle of attack,  $\alpha$ .

2. Describe the process of controlling lateral direction when sideslip is generated.

Lateral-directional control of the orbiter is maintained by the combined use of yaw jets, ailerons, sideslip angle, and the rudder (when it is active) to produce bank maneuvers during entry. The sideslip is then damped by yaw rate feedback to the ailerons.

3. Describe the difference between early and late regions of lateral-directional control.

At Mach numbers above 3.5, bank maneuvers are initiated in the yaw channel, and the roll channel provides coordination and damping. At Mach numbers between 4.0 and 0.9, there is a gradual change from yaw channel bank maneuver initiation to roll channel initiation, with coordination coming from the yaw channel.

4. Describe the significance of GALR.

GALR is the mechanism that makes the transition from early to late entry possible. GALR gain conditions the roll rate command and, by controlling the sign of the command, blends the transition.

5. What condition(s) must be satisfied for the shuttle to be trimmed?

For the shuttle to be trimmed, the aerodynamic moments about an axis or set of axes must be zero.

6. List the lateral-direction control effectors for trim.

Ailerons, yaw jets, sideslip angle, and the rudder are lateral-direction control effectors.

7. State when the rudder becomes active for trim.

The rudder becomes active for trim at Mach 5.

**SECTION 4**1. When are roll jets deactivated?

Roll jets are deactivated when  $\bar{q} = 10.0$ .

2. When are the ailerons active for control?

Ailerons are active for control when  $\bar{q} = 2.0$ .

3. What is the consequence of GALR decreasing from 1.1 to 0.0?

The roll rate command is becoming increasingly proverse and dominant in determining the aileron response. Through GALR gain reductions, the aileron response is transitioning from  $\beta$  damping to performing conventional roll maneuvers.

4. Describe auto load balancing.

Following touchdown, the ailerons begin to receive commands to attempt to balance the loads between the main tires.

## SECTION 5

1. What is the driving parameter in the yaw channel for most of the entry?

For most of entry, the driving parameter in the yaw channel is the bank rate command.

2. When does the rudder become active?

The rudder becomes active at Mach 5.



**SECTION 6**

1. State actions required in case the WOW discrettes or WONG discrettes are not set automatically.

If the WOW or WONG discrettes are not set, the crew must use the ET or SRB SEP switch and pbi to set landing discrettes. Per the Entry Maneuvers cue card set the SRB SEP switch to MAN/AUTO and depress the SEP pbi.

2. State how load relief is accomplished when landing in CSS P.

If CSS P, The DAP will mode to AUTO P when the load relief flag is set. Automatic commands will then drive the elevons 10° down, biased for auto load balancing, for load relief.

## SECTION 7

### 1. When is NWS active?

In either Roll/Yaw AUTO or CSS, once the GSENL flag is set NWS will be active if the NWS power switch is set to NWS 1 or 2.

**SECTION 8**1. When is the aerojet DAP initialized?

Entry DAP is initialized by the crew typing OPS 304 PRO, transitioning the flight software to MM304.

2. When do the RCS activity lights reconfigure?

RCS activity lights reconfigure when  $\bar{q} = 50$  psf.

3. When are the roll, pitch, and yaw jets deactivated?

Roll, pitch, and yaw jets are deactivated at  $\bar{q} = 10$  psf,  $\bar{q} = 40$  psf, and Mach 1.0, respectively.

## SECTION 9

1. Using Figure 9-1, at what point does the crew take CSS to begin manually flying the orbiter?

Mach less than 1.0,  $M < 1.0$ .

2. Using Figure 9-2, find the following for Mach 17:

- a. Reference alpha                    40°
- b. Range                                    857 n.mi.
- c. Attitude                                197,000 feet
- d. Vertical velocity ( $\dot{H}$ )                189 fps
- e. Bank angle                              62° left bank

**SECTION 10**

1. State the three entry DAP software conditions that can be seen on PASS GNC SPEC 51, OVERRIDE.

The three aerojet software conditions that can be seen on PASS GNC SPEC 51, OVERRIDE, are

- a. AUTO or FIXED elevons
- b. NOM or ALT body-bending filters
- c. Software status of entry mode switch

2. State how to change the software status of the Entry mode switch back to AUTO if the switch is physically stuck in NO Y JET or LO GAIN.

To change the software status of the Entry mode switch back to AUTO if the switch is physically stuck in NO Y JET or LO GAIN, type in ITEM 42 EXEC on PASS GNC SPEC 51, OVERRIDE.

## SECTION 11

1. State the purpose of PTIs.

PTIs provide automatic test maneuvers during flight to obtain flight data from which aerodynamic coefficients can be extracted postflight. These data might define characteristics to allow expansion of the operational envelope and reduction of aero database uncertainty.

## SECTION 12

### 1. Why are there differences between nominal entry DAP and GRTLS DAP?

The main reason for differences between entry DAP and GRTLS DAP are gain reductions in GRTLS compared to nominal entry. Gain reductions are made to account for heavier return weight, different angle of attack versus Mach number profiles, and higher anticipated dynamic pressures.

## TRAINING MATERIALS EVALUATION

Please answer the following questions regarding the lesson you just completed. Your feedback will allow us to produce more effective training materials. When completed, mail to: Manager, DT34.

**TITLE/CODE OF LESSON:** Entry Digital Autopilot Workbook/ENTRY DAP 21002

**SIZE OF AUDIENCE/CLASS:**

### 1. How well did this lesson meet its purpose?

For each statement below, mark one box on the scale:

- a. *The lesson objectives are clearly stated.*
- b. *The lesson objectives are clearly defined.*
- c. *The lesson effectively teaches skills and information.*
- d. *The lesson meets its purpose and objectives.*

Strongly Disagree				Strongly Agree			
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

### 2. How satisfying is the content of this lesson?

For each statement below, mark one box on the scale:

- a. *The information is structured in a logical flow.*
- b. *The content is clear.*
- c. *The content is complete.*
- d. *The level of detail is correct for this information.*
- e. *The amount of information is effective.*
- f. *The graphics contribute to my understanding.*

Strongly Disagree				Strongly Agree			
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

### 3. How appealing was the presentation of this lesson?

For each statement below, mark one box on the scale:

- a. *The overall presentation is appealing.*
- b. *The visuals chosen are appropriate for the lesson.*
- c. *The visuals make the information more interesting.*
- d. *The graphics are legibly reproduced.*
- e. *The audio/visual or print quality is good.*

Strongly Disagree				Strongly Agree			
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

### 4. How valuable is this information?

For each statement below, mark one box on the scale:

- a. *The lesson teaches skills and information I need.*
- b. *The lesson meets my expectations.*
- c. *This information is useful for later reference.*
- d. *I would recommend this lesson to others.*

Strongly Disagree				Strongly Agree			
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

**PLEASE WRITE YOUR COMMENTS/QUESTIONS ON THE BACK OF THIS FORM.  
EXPLAIN ANY NEGATIVE ANSWERS IN SPECIFIC TERMS.  
THANK YOU IN ADVANCE FOR YOUR ASSISTANCE!**



TITLE: Entry Digital Autopilot Workbook

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