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CREW PROCEDURES EVALUATION SIMULATOR

ENTRY FLIGHT CONTROL SYSTEM DOWNMODING EVALUATION FINAL REPORT

FEBRUARY 24, 1978

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ABSTRACT

The concept of downmoding was approved in August 1977 as a method to desensitize the entry flight control system to structural vibration feedback which might induce an oscillatory instability. Although the complexity of modeling structural dynamics on a real-time simulator precluded the evaluation of the downmoding scheme in the presence of structural resonance feedback, the general characteristics and capabilities of a proposed scheme suggested applications to a variety of situations having the possibility of occuring in flight. Trends in vehicle response and handling characteristics as a function of gain combinations in the FCS forward and rate feedback loops are described as observed in a man-in-the-loop simulation. Among the flight conditions considered are the effects of downmoding with APU failures, off-nominal trajectory conditions, sensed angle of attack errors, the impact on RCS fuel consumption, performance in the presence of aero variations, recovery from large FCS upsets, and default gains.

This study demonstrated that the capability to modify the entry FCS gains in a predictable fashion provides a flexible tool for coping with off-nominal or off-design conditions such as may be encountered during the flight test program. It further indicates that unambiguous cues and specific responses can be defined which permit the pilot to confidently execute these FCS reconfigurations in accordance with the applicable mission rules.

ACKNOWLEDGEMENT

We wish to express our appreciation to Mr. Michael Keeler for his enthusiasm, dedication, and patience throughout this evaluation. Mr. Keeler devoted much of his otherwise free time, whenever possible, to ensure that impromptu software modifications were implemented with all expediency.

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1.0 EVALUATION BACKGROUND

Components of rates sensed by Orbiter gyros may be attributed to structural flexure and, therefore, be oscillatory in nature. Due to the complexity of bending analysis and aerodynamic predictions there is always the possibility that some modes may not be compensated for by the flight control system body bending filters, thus allowing the possibility of a vehicle-flight control system interaction. A means of providing protection against an oscillatory divergence is desired. One proposed method, i.e., DOWNMODING, allows a real-time capability to manually alter flight control system gains through switch-activated gain multipliers.

The required crew interface controls were defined and baselined for incorporation into the OV102 vehicle. However, the corresponding flight software necessary for the switch functions was not available at the time the system hardware was approved.

The Crew Procedures Evaluation Simulator (CPES) subsequently became available for a qualitative evaluation of the proposed software modifications to the entry FCS. Therefore, CB and CG5 proposed a software mechanization that might provide insight into the characteristics associated with a downmoding scheme and some of the applicable flight techniques. It is hoped that the results of this evaluation may stimulate new questions and may be of interest particularly to those involved in producing software to support upcoming FCS FSSR updates.

The entry FCS downmoding modification includes a reconfiguration module to establish specified combinations of the AUTO, CSS, and GAIN ENABLE (downmoding select) modes. The pilot is able to selectively change the forward loop and rate feedback loop gains in each axis through the three-position panel mounted switches. Rate feedback gains can be reduced incrementally to zero gain to provide a pseudo-manual direct capability. Forward loop gains can be either reduced or increased as a function of the panel switch positions to improve handling qualities. Appendix A contains the modified entry FCS FSSR block diagrams as implemented in the CPES for pilot evaluation.

The evaluation philosophy adopted for this entry simulation test was twofold; first, to establish trends in handling qualities with respect to combinations of forward loop and rate feedback gains under nominal trajectory conditions, and secondly, to investigate the application of the proposed downmoding scheme to specific problems involving fixed gains, angle of attack biases in flight control, aero variations, APU failures, RCS fuel consumption, and flight techniques for the rate-feedback-off, "pseudo manual-direct" mode. Due to the complexity of modeling structural dynamics, model verification, data availability and simulator limitations, the downmoding concept was not evaluated under conditions of structural vibration feedback. No off-line stability analysis was performed to specifically determine the optimum gain magnitudes or their placement in the software. Therefore, the evaluation emphasizes qualitative rather than quantitative results. Sections follow which discuss the evaluation objectives as stated in the original test plan, and the application of downmoding techniques to some specific flight control areas.

2.0 CPES UTILIZATION

Checkout of the FCS Downmoding modifications was begun on June 8, 1977, and the evaluation was terminated on December 15, 1977. During that period 84.5 hours were devoted to checkout, sim model verification, implementation of additional simulator modifications, troubleshooting, and production runs. For a complete description of the CPES configuration please refer to Appendix C.

The pilot evaluators representing the Astronaut Office were Col. H. W. Hartsfield and Cmdr. T. K. Mattingly.

3.0 SUMMARY OF CONCLUSIONS

1. Response trends for the forward loop and rate feedback gain combinations in each axis were as expected with nominal aerodynamics. Generally, response improved with an increase in the forward loop gains and degraded with a decrease in those gains. With reductions in feedback gains, damping became slower, usually demonstrating oscillatory tendencies. (Section 4.1)

2. Surface or body rate oscillations induced by the combination of the effects of aero variations and an overgained FCS at high $\overline{q}$ were most often damped by reducing the feedback gains. (Section 4.2)

3. When APU failures coupled with executing pitch and roll maneuvers invoke PRL, a reduction of the rate feedback gains can ease the FCS workload, improving damping by diminishing surface rate limiting and vehicle oscillations. (Section 4.3)

4. Below Mach 12.5 the three combinations of gain multipliers used to determined RCS fuel consumption all required approximately the same amount of fuel to accomplish specific maneuvers. Since the use of the downmoding gains did not change the impulse requirements, it appears that any RCS propellant conservation will have to come from more efficient firing times or from RCS/aero interactions. (Section 4.4)

5. At Mach 13 off-nominal trajectory conditions did not seem to dramatically affect responses of any of the gain combinations. At Mach 4, however, control of angle of attack was most critical. Generally, any reduction in feedback gains aggravated oscillations, which in some instances became divergent. (Section 4.5)

6. Of the runs made to determine the effects of fixing Mach, angle of attack, or dynamic pressure inputs to the flight control system, angle of attack was again the most critical parameter. Roll performance is dramatically affected by incorrect knowledge of α. (Section 5.1)

7. The proposed $\bar{q}$ vs. velocity schedule for default gains was found to provide satisfactory control if the true α was near the fixed angle of attack. The vehicle response appeared to be insensitive below Mach 2 to rather gross errors in dynamic pressure. A fixed angle of attack (12°) and dynamic pressure (200 psf) was found to improve performance in the presence of aero variations over the $\bar{q}$ vs. V schedule. (Section 5.1)

8. Errors in the angle of attack input to the flight control system produce a number of symptoms which can be interpreted to determine the sign of the error and the appropriate corrective action. The countermeasures so developed are useful even in the presence of aero variations. Downmoding to low rate feedback gains can improve damping, and even avert a loss of control, for cases with negative α errors. (Section 5.2)

9. Downmoding to zero rate feedback gains produces a pseudo manual direct capability. Manipulation of the forward loop gain switches can improve handling qualities, depending on the current dynamic pressure regime. Even so, special pilot techniques are required for this control mode. (Section 5.3)

10. A technique using manual direct reverse aileron commands to command roll maneuvers and enabling the CSS feedback loop to damp β wihtout RCS jets has been demonstrated to allow minimum RCS entries. (Section 5.4)

11. Once diverging rates and attitudes as a result of an FCS instability have been established, downmoding both the pitch and roll axes to low forward loop gains and low rate feedback gains allowed control to be regained. As the motions cease to diverge, increasing the gains will improve damping and restore full control authority. (Section 5.5)

12. Gross errors were introduced individually in the coefficients $C_{n\beta}$, $C\ell_\beta$, Cy_β, and Cn_{δ_a} and were found to not significantly affect vehicle response. Large increases in Cm_{δ_e} and $C\ell_{\delta_a}$ produced rapid pitch and roll oscillations, respectively, which could be immediately damped by downmoding to either low forward loop or low rate feedback gains. (Section 5.6)

4.0 DOWNMODING RESPONSE CHARACTERISTICS

4.1 RESPONSE TRENDS AT NOMINAL TRAJECTORY CONDITIONS

What differences are noted between the vehicle handling characteristics with the nominal gain structure and those with combinations of forward loop and rate feedback loop gain multipliers as selected by the panel-mounted switches? Does any combination of the proposed gains produce an uncontrollable or otherwise objectionable vehicle response to stick commands along the nominal OFT-1 trajectory for the OFT-1 vehicle configuration and nominal aero?

Method: During the initial evaluation period six sets of forward loop and rate feedback loop gain combinations were examined along the OFT-1 preliminary reference flight profile. The vehicle configuration included a mid X c.g. at 1092.8 inches, no Y c.g. offset, and a gross weight of 184,000 lbs. with nominal aero. Generally, the forward loop and rate feedback gain combinations were examined on an independent axis basis. The pilot task for the roll axis was to command a maximum rate roll doublet and center the RHC; the manuever was to be executed with the nominal FCS gains and then repeated after switching to the desired combination of roll axis forward loop and rate feedback gains. Pitch axis doublets were commanded only $\pm 2°$/sec rather than max rate, but again a doublet was executed with nominal gains and then followed by a doublet executed with a desired gain combination. Comparison of the gain combinations vs. nominal FCS gains were made in five Mach regimes. The pilot was to observe response time, maximum rates achieved, and damping characteristics.

Results: Table I (pages 9 to 11) is a summary of the vehicle handling characteristics with selected combinations of gain multipliers as compared to characteristics exhibited with the nominal FCS gains. Mach dependent comments are recorded from high Mach numbers to low.

Although no control losses were experienced with nominal trajectory conditions, the combination of low forward loop and low rate feedback gains exhibited very slow response and damping. For normal control this might seem objectionable, but this same characteristic can be advantageous in some instances, e.g., reducing surface rate limiting with APU failures, as will be described later. Lateral-directional control was marginal in the pseudo-manual-direct configuration, i.e., with zero rate feedback, requiring special pilot techniques, highly dependent upon pilot proficiency, to maintain control. Pitch control with the rate feedback "OFF" required constant attention but was relatively easy to control. A further discussion of the manual direct capability is contained in Section 4.3.

TABLE I. DOWNMODING RESPONSE TRENDS SUMMARY

PITCH FORWARD LOOP GAINS			PITCH RATE FEEDBACK GAINS			ROLL/YAW FORWARD LOOP GAINS			ROLL/YAW RATE FEEDBACK GAINS			TREND RESULTS AS COMPARED TO NOMINAL GAIN RESPONSES
2	1	1/2	2/3	1/3	0	2	1	1/2	2/3	1/3	0	
	X		X									LITTLE CHANGE IN RESPONSE TO COMMANDED PITCH DOUBLET OVER NOMINAL SYSTEM. IN SOME CASES DAMPING WAS DEADBEAT, THOUGH SLOWER THAN NOMINAL. ANY RATE OVERSHOOTS WHILE DAMPING WERE FEWER IN NUMBER AND OF LESS MAGNITUDE WITH THE REDUCTION IN FEEDBCK GAINS.
	X			X								RESPONSE TO DOUBLET WAS SLOWER IN THE EARLY ENTRY FCS WITH DEADBEAT DAMPING WHICH WAS ALSO SLOWER THAN NOMINAL IN THE MACH 2.5-1.8 REGIME. IN THE LATE FCS, PARTICULARLY M1.5-1.0, RESPONSE WAS SLOWER AND OSCILLATORY; DAMPING WAS ALSO POORER THAN NOMINAL, BEING OSCILLATORY WITH SEVERAL OVERSHOOTS.
X			X									RESPONSE IS SNAPPIER THROUGHOUT THE FLIGHT REGIME ALTHOUGH BECOMING OSCILLATORY IN THE MACH 2.5-1.8 REGION. DAMPING IS IMPROVED AT MACH 25 OVER NOMINAL, BUT BECOMES POORER AND MORE OSCILLATORY AS MACH DECREASES IN THE EARLY SYSTEM. IN THE LATE SYSTEM, $M \leq 1.5$, RESPONSE IS QUICK; DAMPING IS ALSO QUICK AND DEADBEAT.
X				X								IN THE EARLY SYSTEM RESPONSE WAS SLIGHTLY SLOWER THAN NOMINAL WITH SLOW, DEADBEAT OR SMALL-AMPLITUDE OSCILLATORY DAMPING. IN THE LATE SYSTEM RESPONSE WAS STILL SLIGHTLY SLOWER WITH GOOD DAMPING BELOW MACH 1.5.
		X	X									VERY SLOW TO EXTREMELY SLOW RESPONSE OBTAINED IN THE EARLY SYSTEM; AS MACH DECREASES, SLOW, DEADBEAT DAMPING BECOMES A VERY LONG-PERIOD OSCILLATION BELOW MACH 3. RESPONSE WAS VERY SLOW IN THE LATE SYSTEM WITH POOR DAMPING. FIRST PITCH RATE OVERSHOOT WAS TO 1.5 DEG/SEC WHEN THE RHC WAS CENTERED.

TABLE I. DOWNMODING RESPONSE TRENDS SUMMARY
(Continued)

PITCH FORWARD LOOP GAINS			PITCH RATE FEEDBACK GAINS			ROLL/YAW FORWARD LOOP GAINS			ROLL/YAW RATE FEEDBACK GAINS			TREND RESULTS AS COMPARED TO NOMINAL GAIN RESPONSES
2	1	1/2	2/3	1/3	0	2	1	1/2	2/3	1/3	0	
		X		X								VERY SLOW RESPONSE WITH SLOW, SMALL-AMPLITUDE OSCILLATORY DAMPING IN EARLY FCS. EXTREMELY SLOW RESPONSE IN THE LATE SYSTEM WITH POOR DAMPING. FIRST RATE DAMPING OVERSHOOT TO 2 DEG/SEC.
							X		X			WITH NOMINAL GAINS RESPONSE WAS CRISP AND DAMPING IMPROVED AS MACH DECREASED. LOWERING THE FEEDBACK GAINS SLOWED THE RESPONSE. DAMPING WAS OSCILLATORY, BEING WORST AT MACH 3, BUT IMPROVED TO BEING DEADBEAT IN THE LATE SYSTEM BELOW MACH 1.5. RESPONSE WAS SLOWER IN THE LATE SYSTEM ALSO.
							X			X		RESPONSE BECAME EVEN SLOWER THAN WITH THE NOMINAL-MEDIUM GAIN COMBINATION AS MACH DECREASES. DAMPING WAS POORER THAN NOMINAL WITH WORST OSCILLATIONS OCCURRING IN THE MACH 4-3 REGION, SUBSEQUENTLY IMPROVING UNTIL BECOMING DEADBEAT BELOW MACH 1.5.
						X			X			IN THE EARLY SYSTEM, MACH 25 AND BELOW, THE ROLL RESPONSE TIME WAS NEARLY NOMINAL, BUT THE RATES WERE MORE OSCILLATORY. AGAIN, DAMPING WAS OSCILLATORY, WORST BETWEEN MACH 4 AND 3, BECOMING SLOW AND DEADBEAT BELOW M = 1.5. RESPONSE IMPROVED, BECOMING FASTER THAN NOMINAL, IN THE LATE SYSTEM.
						X				X		AT HIGHER MACH NUMBERS RESPONSE WAS SLIGHTLY FASTER THAN NOMINAL, BUT DEGRADED TO BEING SLIGHTLY SLOWER THAN NOMINAL BELOW M = 2.5. DAMPING, ALSO, CONTINUED TO DEGRADE UNTIL OVERSHOOTS OF 9°/SEC WERE OBTAINED IN THE MACH 3 REGION. RESPONSE IN THE LATE FCS WAS NEARLY NOMINAL, BUT DAMPING WAS VERY SLOW (DEADBEAT) AFTER CENTERING THE RHC.

TABLE I. DOWNMODING RESPONSE TRENDS SUMMARY
(Continued)

PITCH FORWARD LOOP GAINS			PITCH RATE FEEDBACK GAINS			ROLL/YAW FORWARD LOOP GAINS			ROLL/YAW RATE FEEDBACK GAINS			TREND RESULTS AS COMPARED TO NOMINAL GAIN RESPONSES
2	1	1/2	2/3	1/3	0	2	1	1/2	2/3	1/3	0	
								X	X			SLIGHTLY SLOWER ROLL RESPONSE WITH SMALL AMPLITUDE OSCILLATIONS FOR A STEADY-STATE INPUT AT M = 12. AT MACH 4 THE MAXIMUM COMMANDED STEADY STATE ROLL RATE OVERSHOT TO 5.5°/SEC. SLIGHTLY POOR, SMALL AMPLITUDE OSCILLATIONS WHILE DAMPING, THOUGH ACCEPTABLE, IN THE EARLY FCS. IN THE LATE SYSTEM, RESPONSE IS ONLY SLIGHTLY SLOWER THAN NOMINAL; DAMPING IS SLOW, DEADBEAT.
								X		X		SLIGHTLY SLOWER RESPONSE WITH OSCILLATORY RATES FOR COMMANDED STEADY STATE INPUT. 7°/SEC ROLL RATE OVERSHOOT AT MACH 4 POINT WITH INITIAL COMMAND. DAMPING WAS VERY POOR AND OSCILLATORY AT MACH 12 BUT IMPROVED UNTIL BECOMING SLOW AND DEADBEAT IN THE LATE FCS.

4.2 DOWNMODING WITH AERO VARIATIONS

What combinations, if any, of forward loop and rate feedback loop gain multipliers reduce or stop surface and/or body oscillations caused by aero variations? Which combinations improve handling qualities in the presence of aero variations for "IFCS stress cases"?

Background: Preliminary results of the SPS FCS stress sim conducted in October and November, 1977, as well as previous simulations, indicated that surface and body oscillations could occur with combinations of aero variations, particularly below Mach 5. Generally, the oscillations occurred only in the roll axis with little pitch coupling.

Method: Data runs were initialized at a Mach 2, 238 psf ($\bar{q}$), initial condition reset point. The pilot allowed the equivalent airspeed to increase to 280-290 kts. With aero variation combination case #12 (best-on-best aero variations for the late FCS) roll ringing was observed prior to Mach 1.5. Highly oscillatory roll rates were noticed below Mach 2 with aero case #14 (δ_A - δ_R crossfeed schedule with α), also.

Results: Enabling the roll-axis downmoding gains and selecting nominal (1.0) forward loop gains and medium (2/3) feedback gains, quickly stopped the roll rate ringing. Several other cases of instability or large amplitude oscillations which were observed on the SPS could not be duplicated to the same severity on the CPES, possibly due to simulator differences such as in actuator and aero models. However, it was felt that the downmoding capability to reduce or stop oscillations induced by inappropriate gains for the flight conditions encountered had been established.

4.3 DOWNMODING INFLUENCE ON PRL

How does Priority Rate Limiting (PRL) as brought about by APU failures and/or high hinge moments affect the choice of gain multiplier combinations?

Background: Maneuvers commanded under FCS stress conditions with 2 APU failures, particularly below Mach 3 where higher dynamic pressures and hinge moments are likely to be encountered, can result in surface rate limiting and vehicle rate oscillations.

Method: The reset point used was again a Mach 2 initial condition. The vehicle configuration included a +1.5" Y c.g. offset with 2 APU's failed. Aero cases #9 (poor Dutch-roll damping) and #12 (late FCS best-on-best aero variations) were examined in the presence of turbulence (CPES model at a scale factor of 1). The pilot task was to command a -2°/sec pitch rate, stabilize, release the RHC and allow to damp, then command a -5°/sec roll rate, stabilize, recenter the RHC, and allow to damp. The task was then repeated in the opposite directions, i.e., pitch up and roll right. Dynamic pressure was maintained from 250 psf to 300 psf. The gain combinations evaluated were as follows:

	FORWARD LOOP	RATE FEEDBACK LOOP
1. PITCH AND ROLL/YAW	NOMINAL	MEDIUM
2. PITCH AND ROLL/YAW	LOW	MEDIUM
3. PITCH AND ROLL/YAW	LOW	LOW

Results: In general, a reduction in the rate feedback gains diminished the steady-state oscillations present after a commanded input. More importantly, surface rate limiting was reduced and damping improved somewhat. By reducing the flight control system workload, the APU fuel consumption should also decrease, although no specific data was obtained to support this conclusion.

4.4 RCS FUEL CONSUMPTION

Does downmoding affect the RCS usage?

Background: In view of limited RCS fuel reserves it was desirable to determine the trends in consumption with respect to gain changes. Perhaps a corollary to the above question would be, "Can a significant saving in the RCS fuel usage be achieved?"

Method: Yaw jet firings (both number of jets and firing duration) had been noted in runs made previously to investigate the application of downmoding to APU failures. A simulator model "patch" was programmed to calculate the RCS fuel consumed during a roll maneuver and that required to damp rates for 5-10 sec. after the RHC was returned to detent and display the time history on a strip chart recorder. Roll maneuvers as described below were executed from three reset points. Runs were repeated for each point for three gain combinations, i.e., nominal forward loop and rate feedback gains, low forward loop and low rate feedback gains, and high forward loop and medium rate feedback gains.

RESET:	MACH:	TASK:
01	27.9	Roll right at max rate to $\phi = 60°$, $\alpha = 40°$, reverse at max rate to $\phi = 0°$, and center RHC.
05	12.5	I.C. is at $\approx 50°$ bank, roll right to $\phi = 60°$ at max rate, reverse at max rate to $\phi = 0°$, maintain constant α, center RHC.
13	4.0	Follow pitch and roll guidance error needles for 1 bank reversal after I.C.

Results: The large bank maneuvers at higher Mach numbers may seem unrealistic, but the intent was to establish trends in the propellant usage. At Mach 27.9 the fuel consumption increased with the following order of gain combinations: low forward loop with low feedback gains, medium feedback with high forward loop gains, and nominal gains. At Mach 12.5 the order, again increasing, was: nominal, low forward loop with low rate feedback, and medium feedback with high forward loop. However, the fuel consumption variation between each of these combinations was only 10 pounds. At Mach 4 the fuel consumption with all gain combinations was within 5 lbs. In many runs, it was noted that fewer yaw jets tended to fire with any reduction in the feedback gains, but total firing time increased. Also, several runs made at Mach 4 indicated that the exact fuel usage seemed to be strongly dependent on the angle of attack maintained through the roll maneuver.

4.5 OFF-NOMINAL TRAJECTORIES AND GAIN COMBINATIONS

Are the gain magnitudes selected for downmoding along the nominal trajectory appropriate for off-nominal (e.g., Hi $\bar{q}$, Lo α) trajectory conditions?

Background: The error signals generated in the flight control system which eventually command surface deflections are frequently functions of angle of attack and $\bar{q}$-scheduled gains. Changing the nominal gains by enabling the downmoding gains in the presence of off-nominal combinations of Mach, α, and $\bar{q}$ may reduce stability margins to unacceptable levels. The following describes an attempt to categorize vehicle response trends with respect to Mach number, downmoding gain combinations, high and low angles of attack, and high and low dynamic pressures (as referenced to nominal trajectory values of α and $\bar{q}$ for a given Mach number).

Method: Two Mach regimes were examined, Mach 13-9 and Mach 4-2.5. The α and $\bar{q}$ combinations flown were high $\bar{q}$ and high α, high $\bar{q}$ and low α, low $\bar{q}$ and high α, and low $\bar{q}$ and low α. The pitch and roll/yaw axes were examined independently. The manual direct (rate feedback off) case was not included in this study. Although all other forward loop and rate feedback loop gain combinations were.

At Mach 13, Reset #4, the pilot task was to adjust α to have a positive or negative 4° angle of attack error indicated on the ADI in pitch and to establish a reference bank angle which would maintain the desired dynamic pressure. High $\bar{q}$ was assumed to be approximately 120-150 psf, low $\bar{q}$ to be 50-95 psf. An individual run consisted of establishing the desired test conditions, executing a rate doublet in the particular axis with nominal FCS gains, enabling the desired downmoding gain combination, and repeating the doublet. Maximum rate ($\pm 5°$/sec) doublets were performed in roll, and $\pm 2\ 1/2°$/sec doublets performed in pitch.

The procedure was similar at Mach 4, Reset #13, with the exception that the desired angle of attack was flown by referencing an alpha meter. High $\bar{q}$ cases were from 285 to 320 psf; low $\bar{q}$ cases from 150 to 190 psf. At Mach 4 nominal $\bar{q}$ and α were indicated to be 222 psf and 17°, respectively.

<u>Results</u>: Differences in roll response at Mach 13 did not appear to be significant for any combination of gains, α, or $\bar{q}$. Damping characteristics seemed more sensitive to low α's than any other factor, tending to be more oscillatory than in all other cases. Pitch response and damping did not change dramatically with any gain combinations over the nominal gain characteristics at the test dynamic pressures and angles of attack. Most noticeable was that low forward loop and reduced feedback gains at any $\bar{q}$ or α combination produced somewhat slower response, though not objectionable, and deadbeat damping, whereas the nominal damping was slightly oscillatory.

However, reactions below Mach 4 were more apparent with changes in state conditions. Angle of attack was the most critical parameter to control. If α was maintained above 20° throughout the maneuver for the high α runs with either low or high $\bar{q}$, roll inputs induced large β and roll oscillations, generally greater than $\pm 2.5°$ and $\pm 5°$/sec, respectively, that in all cases except low α and low $\bar{q}$ were neutrally damped or divergent with any reduction in the feedback gains. Oscillations in the roll maneuver were less severe if α was allowed to diminish. Response with nominal forward loop gains was slightly slower with reduced feedback gains than the nominal feedback gains, perhaps due to the automatic reduction in stick gains as proportional to the reduction in feedback gains. High forward loop gains did not result in any significant difference in response time to the initial bank angle command; however, in particularly the high $\bar{q}$ and low α case, the response to the roll reversal command was noticeably quicker than with nominal gains.

To answer the objectives of this section directly would require a "No", since oscillations of rather large amplitudes were experienced with reductions in the feedback gains. Yet, subsequent evaluations have demonstrated the sensitivity of the flight control system to off-nominal angles of attack and input biases. Therefore, considering the severity of the pilot tasks and technique used, particularly in the high α cases, it is felt that the major degradation of stability and control observed can not be completely attributed to the magnitudes of the downmoding gains; although the trends in vehicle response evidenced would indicate a very judicious use of the gain switches.

5.0 DOWNMODING APPLICATIONS

The following sections discuss the application of the downmoding scheme to specific areas concerning flight control system performance. As a result of investigating the subject in each section, new applications for the downmoding capability began to arise, some of which are evaluated and discussed herein.

5.1 DOWNMODING WITH DEFAULT GAINS

Background: The flight control system contains gains which are scheduled as a function of dynamic pressure ($\overline{q}$). If the air data system is not available below Mach 2 to provide a measurement of $\overline{q}$, a pre-programmed, trajectory dependent $\overline{q}$ vs. velocity schedule will be used in flight control to determine gain magnitudes. A series of runs were conducted to evaluate the feasibility of invoking various "fixed gains in the FCS channels during the transonic region. The purpose of this study was to look for cases where fixed or default gains would be inappropriate for flight conditions encountered and evaluate the utility of various downmoding configurations as a real time solution.

Method: The strategy was to fly from I.C. #15 (Mach 3.8) using the OFT-1 configuration with a +1.5" Y c.g. offset. The pilot task was to fly a series of bank reversals while controlling pitch and $\overline{q}$ and to observe the effects of selecting the downmoding gain combinations. It was intended to catalog the effects of fixing various parameters, individually, first with nominal aero, then with selected aero variations. The FCS parameters of interest were M, $\overline{q}$, and α. Additionally, the following proposed default gain schedule was evaluated:

V_{REL} (ft/sec)	$\bar{q}$ (lbs/ft^2)
3000	240
2500	230
1950	210
1450	215
950	190
850	220
600	290
250	100

NOTE: 1) OFT-1 Reference Flight Profile
2) Angle of attack is fixed at 6.5°

Results

Mach Fixed at 1.6: Manual control of the entry FCS mode was required. At Mach 3 the pitch control was very loose, sluggish to accelerate, and exhibited very poor damping. Downmoding to the pitch axis high forward loop and medium feedback gains provided a big improvement. Downmoding was not needed below $\sim$ Mach 3. Roll control was normal until after the FCS mode switch where it was still limited to 5°/sec. Downmoding to roll rate feedback OFF worked very well for high roll rates.

Mach Fixed at 1.4: Pitch and roll control was the same as described above.

Roll Mode Switch: The FCS was left in the rudder/jet mode with fixed Mach from Mach 3.8 to 18,000 ft. MSL. The aileron mode clearly was superior; however, the rudder/jet mode worked surprisingly well between Mach 1.5 and 0.6. The roll response was very "jerky" and would probably be very bothersome in a motion environment; however, controllability was not in question. Downmoding to roll rate feedback LOW and forward loop HIGH improved performance. Angles of attack between 5° and 15° were evaluated without any noticeable change in characteristics.

Angle of Attack Fixed at 10°: Roll response and β were not as tightly controlled; however, there was not a requirement to alter the configuration. True alphas between 15° and 3° were evaluated.

Angle of Attack Fixed at 6.5°: Above Mach 3 the roll rate was reduced to about 2°/sec, β ranged between +2° and -1.5°, with two jets on continuously during maneuvers. The low roll rate was partially caused by multiplying the RHC command by the sine of α in AXEDCOMP. A gain of 3.0 was applied to this command. This provided more roll but resulted in much larger values of β. Downmoding did not help and could make it worse.

Angle of Attack Fixed at 15°: This improved the roll performance supersonically but did not control β as tightly. Downmoding did not help and did result in a subsonic loss of control with low roll rate feedback gains and low α.

Evaluation of Proposed $\bar{q}$ vs. V Schedule: This case created very low roll rates above Mach 2. Direct yaw jets (RCS wraparound mod) were used but were not effective because the FCS reduced command was fighting the actual yaw rate. The scheme does work well when α is near nominal. Very high $\bar{q}$ and very low $\bar{q}$ conditions were examined with no noted performance change. Changing to other fixed α values improved the $M > 2$ performance slightly.

In the presence of aero variations (Sets #16 and #11) there was no roll response at true α's greater than 15°, and surface trim saturated. For example, a given max rate roll command would force 10° right rudder, 4° right aileron deflection, and two right yaw jets on continuously. Downmoding did not affect roll response any. If α was fixed to 10° (formerly 6.5°), about a 2°/sec roll rate could be achieved. For the purposes of experimentation angle of attack was fixed at 12° and $\bar{q}$ at 200 psf, which resulted in better performance than the scheduled gains with variation set #11, although control was lost at an α of approximately 3°. Dynamic pressures from 100 to 300 psf were examined with no obvious $\bar{q}$ effects noted. This configuration (12°α, 200 psf $\bar{q}$) was also flown with nominal aero for comparison. Pitch performance was slightly degraded but was improved by downmoding to low feedback gains with nominal forward loop gains.

5.2 α ERRORS AFFECTING THE ENTRY FCS

Background: During aero variation effects studies conducted at Langley, it was noted that feeding an incorrect α estimate to the FCS produced some very undesirable characteristics. This same tendency was observed during our investigation of default gains in the supersonic regime. It was also noted during the evaluation of downmoding characteristics that altering the forward loop gains could change the sign of residual β's associated with prolonged steady state roll reversals. These observations suggested that appropriate selection of roll/yaw downmoding options might provide a practical solution to the case when the α estimate is grossly in error.

Method: The first step was to investigate the reliability of various dynamic responses in identifying and/or isolating an α error. Once the appropriate signature was identified, the second step was to devise effective countermeasures. The final step was to investigate other variations and conditions singly and in concert with an α error in order to test the uniqueness of the signature and universality of these countermeasures.

The entry FCS uses the α estimate in coordinating the steady state p and r to produce a balanced roll about the stability axis. The proposed downmode scheme adjusts the roll rate error signal sent to the aileron channel in response to the sensed yaw rate, and thus offers the potential to adjust the ratio of p to r.

A simulator patch was implemented which allowed switching in discrete α errors on command in order to aid in evaluating the effects of error magnitudes and signs.

Results:

A. α Error Signatures

1. The dominant effect of α errors is manifested during a steady state roll rather than during zero roll rates or roll accelerations.

2. $\bar{q}$ does not affect the response until RCS authority is taxed.

3. The α error signature was the same at the two principle test points, M = 10.5 and M = 3.5. The magnitude of the characteristic response was generally greater at M = 3.5 than at M = 10.5.

4. The following signatures were identified (without aero variations):

   a. When the α estimate to the FCS is higher than the actual α then:

      o β will be constant and of opposite sign to the roll command.

      o The ADI roll rate will be equal to or greater than the commanded roll rate.

      o The SPI will indicate an aileron trim opposite to the roll command.

      o The rudder will be neutral.

      o Yaw jets will fire opposite to the commanded roll direction.

   b. When the α estimate is less than the actual value then:

      o A steady state β will be observed with the same sign as the roll command.

      o The ADI roll rate will be less than commanded.

      o The SPI will indicate aileron trimmed in the direction of roll.

- o The rudder ($M = 3.5$) will be offset in the direction of roll.
- o Yaw jets will be firing to augment the commanded roll.

5. The same signatures were reproduced with α errors and a 1 1/2" Y c.g. offset.

6. Flying low $\bar{q}$ trajectories with α errors produced a modified signature with unusual post maneuver characteristics. At low $\bar{q}$'s the RCS had enough authority that they pulsed rather than fire continuously. This allowed the RCS/aileron up-down counter function to increment the aileron trim such that as the roll progressed, the β was removed and the p error was balanced with the δ_a trim error, producing a coordinated r and p for the actual α. Once this balanced condition was attained, the roll continued in a normal fashion. The surprise came when the roll was stopped, and the now mistrimmed δ_a was applied. This resulted in a diverging β, which if the $\bar{q}$ was high enough to require a continuous jet firing rather than a pulse, i.e., no trim, a subsequent loss of control resulted.

   It should be noted that the CPES FCS only incremented the δ_a trim on the initial yaw pulse of the first jet. A recent mod proposes to increment the trim on each new jet pulse, i.e, it will trim with one jet on continuously and a second pulsing.

B. Countermeasures for α Errors

1. The direct technique investigated was a switch which would apply

a bias to the FCS α estimate. It was mechanized such that it introduced a discrete bias, with selectable sign, downstream of the original error. To verify that the diagnostic procedures were correct, the corrective bias was set equal in magnitude to the α error. The pilot used the following diagnostic/corrective rule--

> If β, δ_a trim, and jets aid in the roll command, then add the α bias.
>
> If β, δ_a trim, and jets oppose the roll command, then subtract the α bias.

This technique worked very well. Although the signatures are unambiguous, a misapplication of the corrective bias was evaluated. The situation quickly degrades and is a very obvious cue that the procedure was improperly executed. In the cases investigated, the reselection of the proper sign correction always resulted in recovery, if corrective action was applied within a few seconds.

The next step was to evaluate the sensitivity to α error sign and the granularity of the corrective bias. The pilot could unambiguously detect errors of 1° in α. This implied that, to be viable the use of a corrective bias would require the ability to apply it with a granularity of $\sim$ 1°. However, this bias granularity was not evaluated.

2. The second technique evaluated was the use of the roll/yaw downmoding feedback gain selection. Since the present proposal only provides reduced gains, it was only effective in correcting α errors which commanded excessive body roll rates, <u>i.e.</u>, the FCS

α estimate is less than the actual α. In these cases, selecting the reduced roll/yaw feedback significantly improved the situation.

3. Attempts to manually trim the aileron function with the console surface position trim were very unsatisfactory because of the sensitivity of this function. The only safe technique is to apply a small trim and wait several seconds to observe the response. Any attempt to trim until the β was removed resulted in over corrections which could diverge.

4. The easiest corrective procedure was for the pilot to execute roll reversals in relatively small increments since the α error is manifest only during sustained rolls.

5. The body flap was used to change the δ_e trim position in order to change the aileron effectiveness. Moving the δ_e trim up resulted in a response similar to lowering the rate feedback gains but was not as effective.

C. Identification and Correction in the Presence of Aero Variations

1. The Langley case was used as the basic test condition. The symptoms were very obvious and, since the α error was negative, both the downmoding and corrective bias techniques were effective.

2. A 1 1/2" Y c.g. offset was evaluated. This offset did not affect the results at all.

3. The sign of $C_{n\delta_a}$ was reversed as an arbitrary aero variation. Both the symptoms and corrective action remained unchanged.

Summary:

A. The signature of an α error is unambiguous during steady state roll reversals, with or without Y c.g. offsets and aero variations.

B. An α error of 1° is identifiable.

C. An α error of 2° deserves intervention and 5° can result in a loss of control if not compensated for in some fashion.

D. The downmoding rate feedback gains will correct for a negative α error of up to 5°.

E. Once the α error is identified bank reversals could be executed safely by rolling for short periods of time, stopping and then resuming the roll. (However, this technique would adversely impact trajectory range control.)

F. The RCS/aileron trim can, under selected conditions, build up an unwanted aileron trim during prolonged rolls with α errors. If ignored this condition can result in a loss of control after the roll maneuver has been stopped.

G. Manual trimming of the ailerons is a delicate task which, if done too coarsely, can result in a subsequent loss of control.

H. Applying a corrective α bias can be effective providing it is available in $\sim$ 1° increments.

5.3 MANUAL DIRECT ENTRY FCS

Background: The proposed downmoding implementation has the potential of providing a pseudo manual direct control mode during all flight regimes. This is obtained by selecting the "OFF" feedback gain in the pitch and/or roll/yaw channels. The purpose of this evaluation was to provide a qualitative assessment of the feasibility of this control mode.

Method: To evaluate and simultaneously develop pilot techniques, this problem was tackled by flying either pitch or roll/yaw in direct with the other axis in a nominal control mode. The rationale for this approach was that it appears unlikely that the situations requiring this mode would simultaneously affect both axes. When the roll/yaw rate feedback "OFF" switch position is selected, all EARLY/LATE switches in those FCS channels as indicated in the block diagrams are moded to LATE regardless of current Mach number. Thus, a CSS roll command will produce an aileron deflection, not a yaw RCS jet command. A patch was implemented (RHC RCS "wraparound") which allowed the pilot to command the yaw RCS by displacing the RHC out of detent in yaw. The number of yaw jets fired is proportional to the number of degrees out of detent. The following pilot techniques and tasks were evaluated:

A. Pitch: Pseudo manual direct was engaged by selecting pitch downmode with the rate feedback "OFF". The tasks were to follow the M/α profile and to deviate substantially from the α schedule and return. Only the 66.25% c.g. was evaluated, and auto roll/yaw was employed.

B. Roll/yaw: This condition was created by selecting roll/yaw to downmode with the rate feedback to "OFF". Initial investigations contained no Y c.g. offsets and progressed to evaluation with a 1 1/2 in. offset. The longitudinal c.g. was maintained at 66 1/4%. The pilot technique for commanding a stability axis roll rate was to use either the yaw jets (on RHC yaw axis) or spiked aileron inputs (+ RHC roll to initiate a $- p_s$) to generate a β which would result in a body roll rate as a result of C_{ℓ_β}. This is the manual analog of the old entry FCS system XI mechanization. Once a β had been generated, the pilot attempted to null the β oscillations with discrete aileron inputs. This technique when properly executed results in small β excursions and a residual roll rate. To achieve the β damping function the technique required the pilot to observe the ADI β indicator (driven from the simulator environment in this evaluation) and apply RHC roll commands in opposition to the accelerating β. For example--to generate a left roll about the stability axis the pilot executes the following steps:

- Smooth right RHC roll input and return to null.

- Observe the β needle move out to the right.

- As the β needle begins to return towards zero (from the right), apply a right RHC roll pulse until the β needle approaches zero.

- Wait, with RHC in null, while the β needle reaches its maximum left excursion then apply left roll (into the β needle) while it is returning towards zero.

- Continue this technique until β excursions are roughly $\pm 1/4°$.

- If the technique has been properly executed there will be a residual coordinated roll and yaw rate.

- o Stopping the roll is accomplished in the same manner.
- o When using the yaw RCS to start and stop maneuvers, the RCS is substituted for the initial aileron input with only β damping being accomplished through the same aileron technique.

Results:

A. Pitch - In general this is a very straight forward and reasonable task. The forward loop gain selection capablity made the task easier. The low gains were most comfortable down to M = 5.0 where the "normal" gain was preferred. Trajectory excursions indicated that the preferred forward loop gain was more a function of Mach than of $\bar{q}$. The higher gains could be used advantageously to aid in recovery from large upsets. The console trim was evaluated but found to be too sensitive to be used as anything other than a gross trim device.

B. Roll/Yaw - The first task evaluated was to merely maintain a nominally zero p_S. Pitch was flown in AUTO. The forward loop gains proved to be very important in maintaining a tolerable pilot workload.

The best gains seemed to be "norm" at low $\bar{q}$'s, i.e., less than 100 psf, and "low" at all others. As long as the pilot stays ahead of the situation, the task is accomplishable and repeatable up to 150 psf with moderate concentration. Pilot concentration becomes intense at a $\bar{q}$ of 200 psf. Flight through M = 6 was always in question.

The next task was to start and stop rolls. At $\bar{q}$ < 150 psf the pilot could start, nearly stop or reverse rolls as long as the rates were maintained in the 1 to 2°/sec. range. At the higher $\bar{q}$'s the pilot had to devote most of his attention to $\dot{\beta}$ damping. The use of yaw jets on the RHC yaw axis significantly eased the pilot's task by avoiding the mental process of determining which way he had to deflect the δ_a to initiate a β to create the desired torque, i.e., right yaw jets result in a right p_s. However, the task of $\dot{\beta}$ damping remains the limiting factor in flying a pure manual direct mode at high $\bar{q}$.

To complete this evaluation a Y c.g. offset was evaluated. This aggravated the pilot's task significantly and became unreasonable if the ailerons had not been trimmed when manual direct was invoked.

Changing the elevon trim position up did not substantially improve the pilot's workload, although trimming down could make it much harder. Altered α profiles did not help either. The only pilot technique which seemed beneficial was to employ smaller and longer duration inputs as opposed to larger, quicker spikes.

It was observed that returning to CSS quickly regained control after the pilot had essentially lost control. This led to the next investigation.

Summary:

- o Manual direct control of the pitch axis was a reasonable emergency control mode at the 66 1/4% c.g. throughout the entry envelope. (CH = 5)

- o A heads up attitude can be maintained with manual direct control of the roll/yaw axis below a $\bar{q}$ of 200 psf.
- o At $\bar{q}$ < 150 psf slow rolls of 1 to 2^{o}/sec can be executed.

- The following are Cooper-Harper ratings assigned for the tasks flown:

  CH=8 to fly wings level up to a $\bar{q}$ of $\sim$ 200.

  CH=9 to execute roll maneuvers up to a $\bar{q}$ of $\sim$ 150.

  CH=10 any maneuvers executed above $\bar{q}$ $\sim$ 200.

- NOTE: Relatively few hours of practice were used in preparation for this evaluation. Therefore, these CH ratings might improve with additional exposure; however, they are valid for relative comparisons with other sections of this report.

5.4 MINIMUM RCS ENTRY CONTROL

Background: The work done on roll/yaw manual direct entry control indicated that if an aid in damping the high frequency dutch roll could be devised, then a viable minimum RCS control mode might become practicable. The following schemes were investigated using selected components of the baseline roll/yaw FCS as a way to fly entries after suffering RCS casualties.

Method: The simulated FCS was modified to fire the yaw RCS with the RHC yaw axis out of detent and to avoid firings when either the RHC roll axis commands were used (RHC RCS wraparound initialized) or the CSS modes were active. The pilot technique was to command a stability axis roll by using manual direct ailerons or firing yaw RCS and then use the CSS modes without RCS, to control β during the roll maneuver. Pitch was flown in AUTO.

Results:

A. Roll rates up to 5°/sec. could be confidently started and stopped at $\bar{q}$'s up to 450 psf. The "norm" forward loop gain was preferred.

B. The higher rate feedback gains were preferred. The higher the $\bar{q}$, the more the high feedback gain improved performance. The nominal CSS mode, without RCS, worked best at very high $\bar{q}$'s; however, the downmode 2/3 rate feedback was satisfactory.

C. A 1 1/2" Y c.g. offset was evaluated. With the δ_a trimmed, the pilot could not discern any effects from the offset. A reliable δ_a trim technique was not developed, however.

D. Trim condition which required the elevons to trim up $>$ 10°, resulted in loss of control in the $M \sim 3$ region.

E. Without any aero variations, it was observed that the CSS control mode produces slow roll accelerations but good roll control without any RCS as the Mach approached ~ 3.0.

F. The CSS could not always damp large amplitude dutch roll oscillations without RCS at higher $\bar{q}$'s. These dynamics could be avoided but were introduced to evaluate the control boundaries.

Summary:

A. The use of manual direct aileron inputs to start and stop roll maneuvers with CSS aileron control to damp the $\dot{\beta}$ produced a satisfactory no RCS entry technique in the flight regimes evaluated ($M \sim 18$, $\bar{q} \sim 50$ to $M \sim 2.5$ and $q \sim 150$), CH = 6.

B. The use of yaw RCS on the RHC yaw axis is an easier method of attaining a minimum RCS entry technique when used with CSS control of the ailerons as a $\dot{\beta}$ damper, CH = 5.

C. Large dutch roll oscillations require yaw RCS in order for CSS to reliably damp β at higher q 's.

5.5 LARGE SIGNAL INSTABILITIES

Background: Large signal instabilities have been observed during previous Orbiter simulations under extreme upset conditions. In the past it has been hypothesized that a temporary reduction in FCS gains might enhance recovery and allow subsequent reversion to nominal gains.

Method: The scheme was to do whatever was necessary to excite a FCS instability and then evaluate the effectiveness of various downmoding gains. The CPES was not able to reproduce the high $\bar{q}$, supersonic roll-yaw coupling observed during the SPS entry FCS stress tests. Therefore, the following conditions were used to create a reproducible FCS instability:

- o Aft c.g. (1108.8 inches ℓ_b)
- o 1 1/2" Y c.g. offset
- o Aero variation case #14
- o BF down to trim the δ_e to -12°
- o A pitch error of +5° and a roll error of ~30° was estalished and the AUTO FCS was engaged at M = 2.3.

This combination would consistently establish a coupled p, q, and r divergence.

Results:

A. Downmoding in roll/yaw only did not produce a recovery.

B. Downmoding in pitch only produced a slow recovery.

C. Downmoding in both axes with both feedback and forward loop gains in low provide a fairly rapid reduction in vehicle motion.

D. Once the vehicle dynamics began to damp, increasing the gains speeded up the recovery.

E. The forward loop gains were more effective than the rate feedback gains in damping these large signal instabilities.

Summary:

A. An extreme set of anomalous conditions was required in order to create an FCS instability on the CPES.

B. Downmoding both axes to low forward loop gains and 1/3 rate feedback gains was effective in regaining control. Once the motions ceased to diverge, increasing the gains hastened the final recovery.

C. The forward loop gains are more effective than rate feedback gains in recovering from FCS instabilities.

5.6 GROSS ERRORS IN $C_{y\beta}$, $C_{m\delta_e}$, $C_{n\beta}$, $C_{\ell\beta}$, $C_{\ell\delta_a}$, $C_{n\delta_a}$

Background: The entry FCS is designed to accommodate arbitrary levels of uncertainty in all aero parameters. A qualitative investigation of extreme errors in selected parameters was desired in order to identify those, if any, which might be susceptable to downmoding techniques.

Method: No attempt was made to create reasonable cases. Rather, the objective was to create FCS responses, such as ringing, limit cycling, etc., which could be recognized and corrected by the pilot in real time. The general technique was to multiply various parameters by scalers (1/2 and 1 1/2) and to then stress the FCS by commanding maneuvers under high and low $\overline{q}$ conditions. These aero anomalies were evaluated singly rather than in combination with other variations.

Results:

A. Scaling $C_{y\beta}$ produced no noticeable change in FCS response. This area was of concern due to the use of N_y in the lateral/directional channel below M = 1.5.

B. Scaling $C_{n\delta_a}$ and $C_{\ell\delta_a}$ produced no bothersome characteristics. $C_{m\delta_e}$ was doubled and flown to high $\overline{q}$ which produced a very pronounced pitch oscillation. Downmoding to either low forward loop gains or rate feedback gains immediately stopped the oscillations.

C. Scaling $C_{n\beta}$ and $C_{\ell\beta}$ produced discernable but benign characteristics.

Summary:

A. No responses requiring corrective measures were identified when gross errors in $C_{n\beta}$, $C_{\ell\beta}$, $C_{y\beta}$, and $C_{n\delta_a}$ were introduced singly.

B. Rapid pitch oscillations resulting from increased $C_{m_{\delta_e}}$ and high $\bar{q}$ were immediately stopped by downmoding. Both forward loop and rate feedback gains appeared to be effective. Similarly, roll oscillations result when $C_{\ell_{\delta_a}}$ is grossly too large and can be arrested also by downmoding.

6.0 ADDITIONAL CONSIDERATIONS

This evaluation has addressed the mechanics of downmoding, i.e., the vehicle response as a function of gain combinations in the forward and rate feedback loops with respect to a few known conditions. However, there remain a number of concerns to be discussed which are beyond the scope of reporting the results of this evaluation, but which do have an impact upon the development of flight software for downmoding and its application.

The entry flight control system is currently being modified to accommodate gain schedule changes and even software structure changes as recommended by Rockwell, Honeywell, and as a result of recent FCS stress simulations. FCS performance is sensitive in some areas to the non-linear actuator model used in the SPS stress sim, and this model, too, is being reformulated. The evolution of the FCS will continue to affect the downmoding quantitative response results. It is not yet known how even the downmoding proposal evaluated influences the presently baselined FCS stability margins and performance specifications, since no analyses have been conducted. Even the Orbiter aerodynamic data is currently being updated.

In this simulation the downmoding implementation was observed under conditions contrived for the purposes of evaluation. Therefore, a criteria was not developed to cue the pilot in any random situation that downmoding could alleviate a stability problem, although in specific instances pilot procedures could be defined. Detailed procedures development, handling qualities and system performance requirements specification, and pilot training will require a high fidelity simulation, which implies the presence of a downmoding scheme in the flight software.

7.0 RECOMMENDATIONS

1. The downmoding scheme as developed for this evaluation should be incorporated into the entry aerojet digital autopilot in the absence of any more mature proposal.
2. The selectable gain values should be contained in the flight software "I-load" to accomodate updates resulting from future FCS stability analyses and simulation experience.
3. The downmoding scheme should be evaluated during all future entry FCS simulations.

8.0 REFERENCES

1. Hartsfield, H. W., Downmoding Crew Interface. CB, March 18, 1977.

2. Barnes, H. A., Entry Flight Control System Downmoding Test Plan (CPES). CG5, September 22, 1977.

3. Gamble, J. D., Test Plan for the Flight Control Stress Testing Engineering Simulation to be Performed on the Shuttle Procedures Simulator (SPS). EJ4, September 13, 1977.

4. Rockwell International, OFT FSSR, Part C: Entry Flight Control. SD 76-SH-0007, November 26, 1976.

APPENDICES

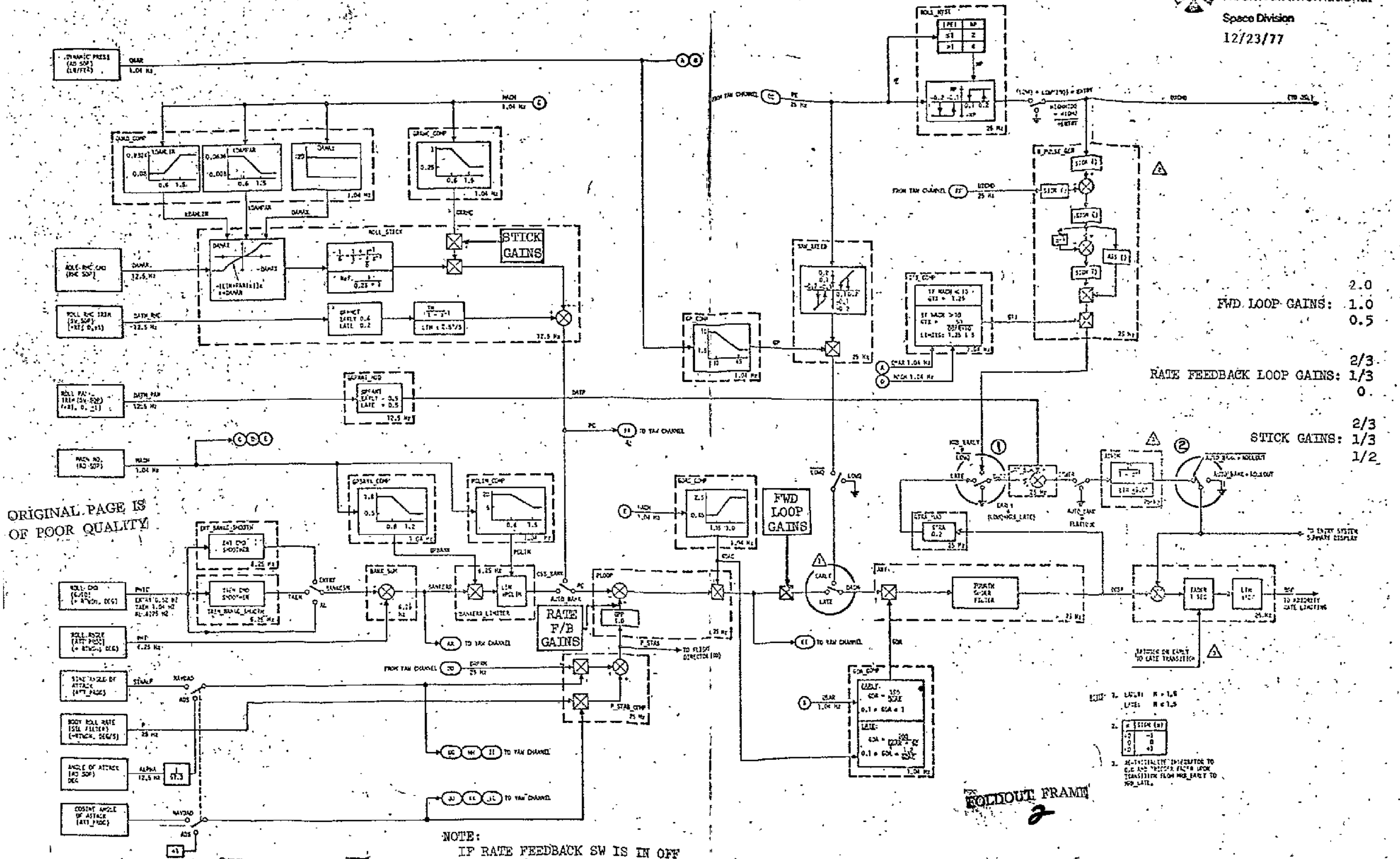
APPENDIX A

APPENDIX A
PROPOSED PLACEMENT OF GAIN MULTIPLIERS IN THE ENTRY
INTEGRATED FLIGHT CONTROL SYSTEM

The enclosed block diagrams from the entry IFCS FSSR depict the position of the forward loop and rate feedback loop multipliers as implemented on the CPES. In addition, the pilot has the option of activating a modification to the RHC modules which allows roll and pitch jets to be fired by placing the RHC at the roll and pitch axes hardstops, respectively. For each axis at the hardstop, four jets are fired as long as the RHC is maintained in that position irrespective of nominal cut-off dynamic pressures. Yaw jets are enabled incrementally from one to four jets depending upon the number of degrees the RHC is out of detent in the yaw axis.

The gain magnitudes stated in the diagrams were those evaluated. Each of these values can be easily specified and changed individually. Once the desired sets of values are specified, combinations of the rate feedback and forward loop multipliers are selected through the panel mounted switches.

Rockwell International
Space Division
12/23/77



NOTE:
IF RATE FEEDBACK SW IS IN OFF POSITION,
- o EARLY/LATE SW'S ARE SET TO LATE
- o SWITCH 1 SET TO GND
- o SWITCH 2 SET TO AUTOBANK • ROLLOUT
- o DON'T ZERO INTEGRATOR

Figure 4.6.5.2-1. Roll Channel Aero/Jet DAP

CREW PROCEDURES EVALUATION SIMULATOR
DOWNMODING CONCEPT

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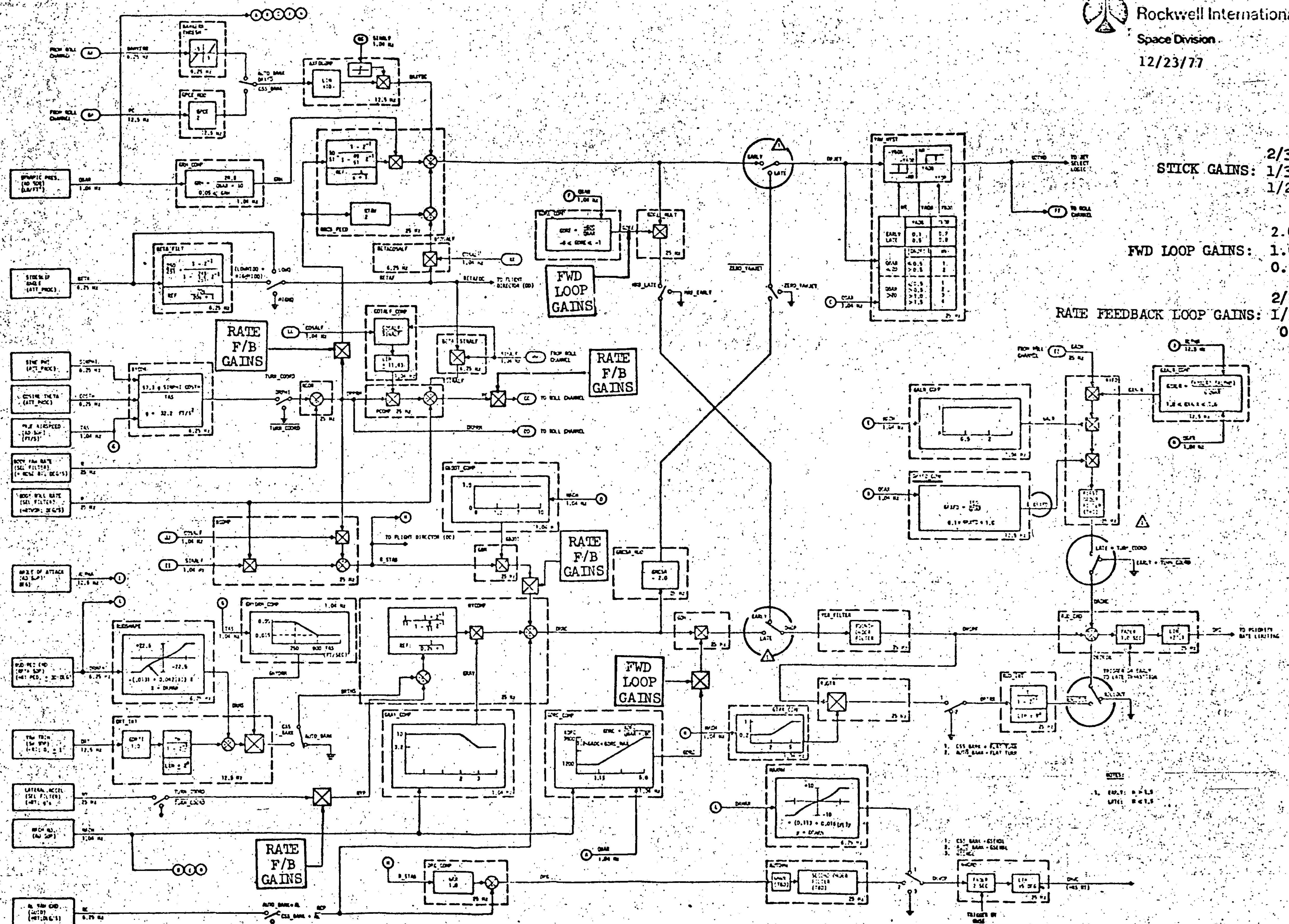

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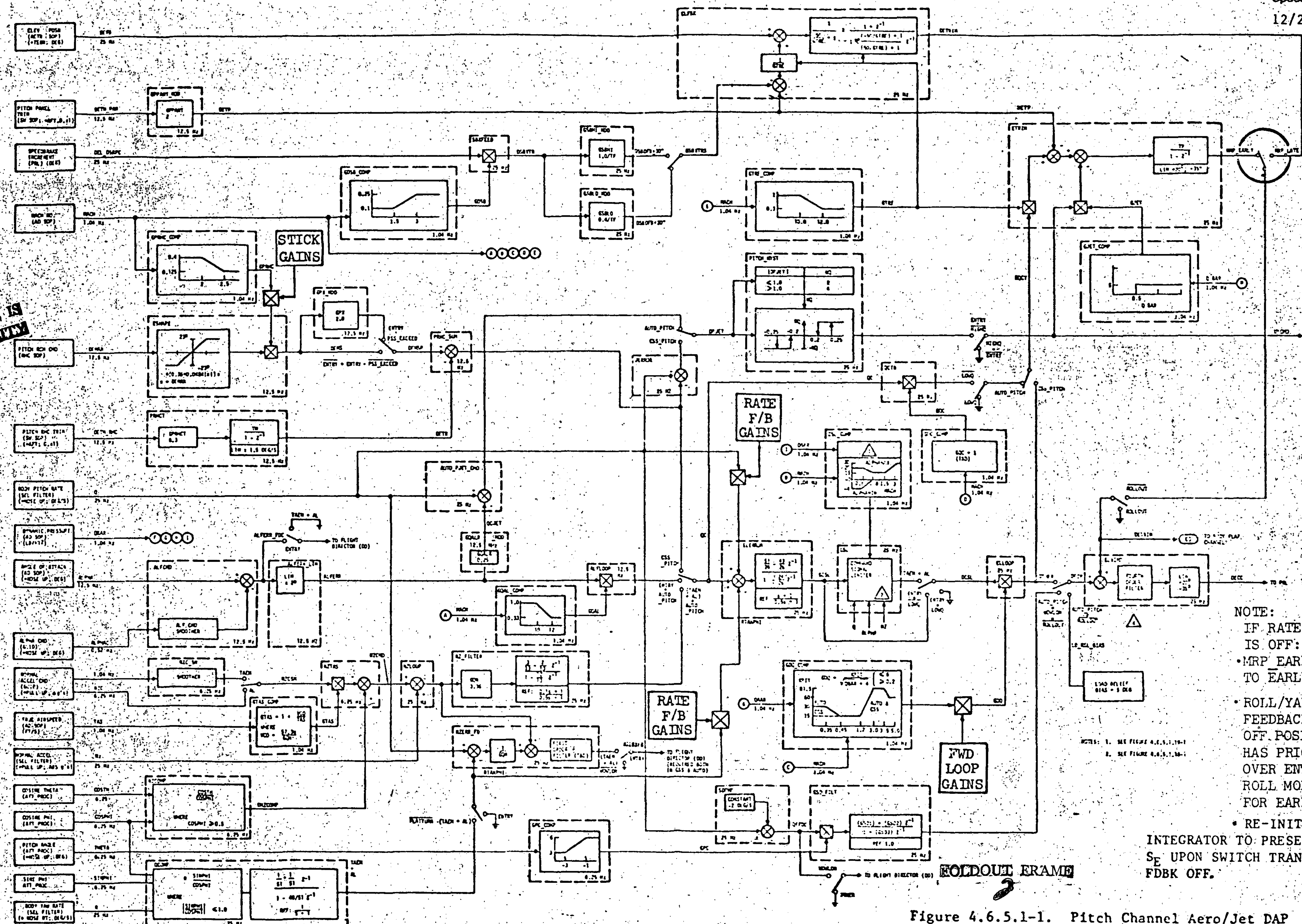
NOTE:
IF RATE FEEDBACK SW IS IN OFF POSITION,
- o EARLY/LATE SW's SET TO LATE
- o TRIM INTEGRATOR SET TO 0 AND OPEN SW TO ROLLOUT
- o GRXFD SET TO 0

FOLDOUT FRAME

Figure 4.6.5.3-1. Yaw Channel Aero/Jet DAP

CREW PROCEDURES EVALUATION SIMULATOR
DOWNMODING CONCEPT

FOLDOUT FRAME



NOTE:
IF RATE FEEDBACK SW IS OFF:
- MRP EARLY SWITCH IS TO EARLY POSITION.
- ROLL/YAW RATE FEEDBACK TO OFF POSITION HAS PRIORITY OVER ENTRY ROLL MODE SWITCH FOR EARLY/LATE.
- RE-INITIALIZE ETRIM INTEGRATOR TO PRESENT VALVE OF S_E UPON SWITCH TRANSITION TO RT FDBK OFF.

FOLDOUT FRAME 2

Figure 4.6.5.1-1. Pitch Channel Aero/Jet DAP

CREW PROCEDURES EVALUATION SIMULATOR
DOWNMODING CONCEPT

FOLDOUT FRAME 1

FWD LOOP GAINS:	2.0 1.0 0.5	RATE FEEDBACK LOOP GAINS:	2/3 1/3 0	STICK GAINS:	2/3 1/3 1/2

RCS JETS ON RHC COMMAND

CPES MECHANIZATION:

A pushbutton (pb) on top of the RHC enabled a software patch to command RCS jets when depressed. A second depression of the pb disengaged the jet command capability. A panel light advised the pilot of the on/off status of the patch.

PITCH and ROLL:

When the software patch is not enabled, pitch and roll jets are fired as defined in the baseline FCS FSSR block diagrams. With the depression of the pb to activate the RHC RCS command, 4 pitch and/or 4 roll jets will be fired, irrespective of $\bar{q}$ limits, if the RHC is at the hardstop of the particular axis. If the RHC is not at the hardstops with the patch enabled, the roll and pitch jets will fire as per the FCS FSSR. In any case, all aerosurfaces are still commanded as indicated in the FSSR.

YAW:

If the RCS command patch is not enabled, no direct control of the yaw axis is possible. Yaw jets are fired for roll and β damping as defined in the FSSR.

If the pb has been depressed, but the RHC has not been deflected out of detent in yaw, the yaw jets will continue to fire as defined in the FCS FSSR.

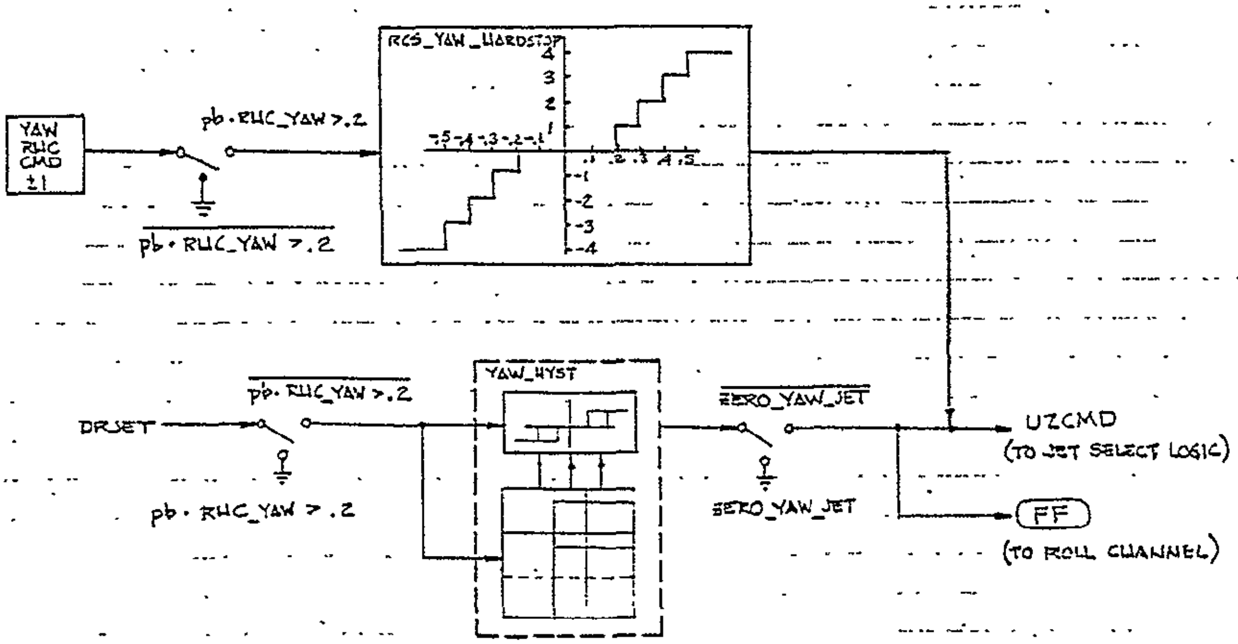
If the RCS command patch has been enabled and the RHC displaced from detent, yaw jets will be fired directly; the number firing being determined by the per cent deflection of the RHC according to the following table:

RHC DEFLECTION	YAW JET COMMAND (UZCMD)	
0.2 - 0.3	1	
0.3 - 0.4	2	(Values shown are
0.4 - 0.5	3	for + Right RHC
0.5 - 1.0	4	deflection.)

- o Full yaw axis deflection is + or -1
- o RHC detent = 0

Yaw jets will not be commanded with roll RHC inputs, if the RHC is deflected out of detent in yaw.

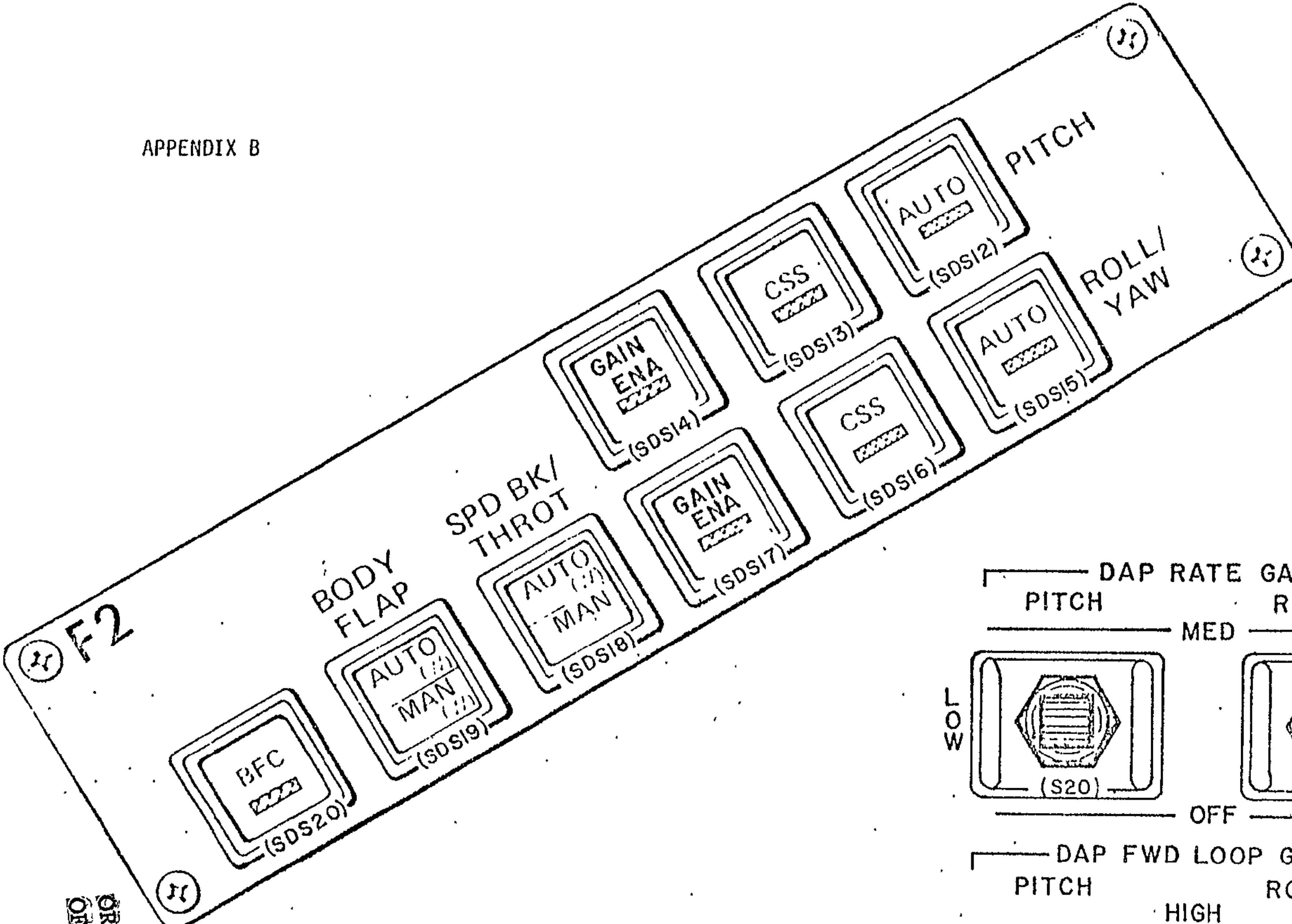
The yaw channel FCS FSSR block diagram is modified as below:

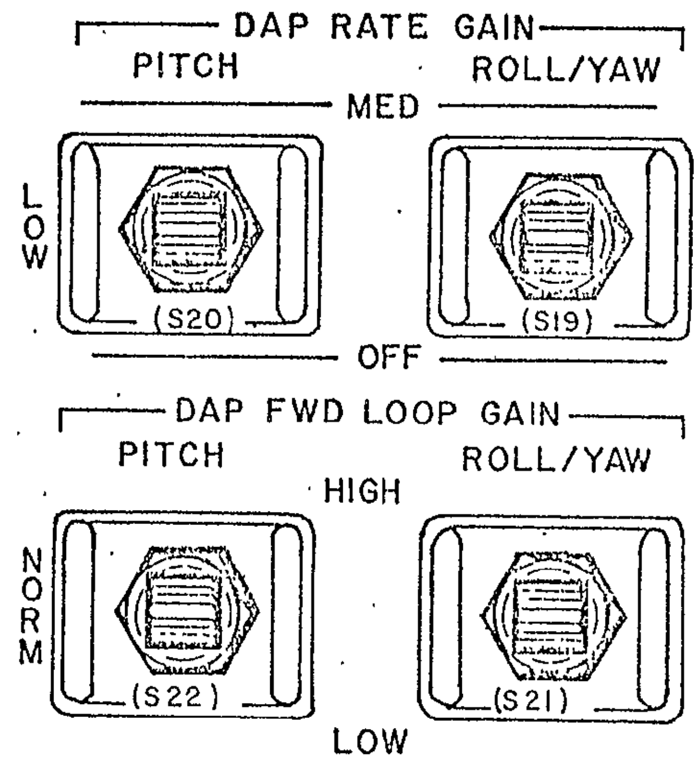


(from Figure 4.6.5.3-1. Yaw Channel Aero/Jet DAP)

APPENDIX B

APPENDIX B





FCS DOWNMODING

SWITCH HARDWARE CONFIGURATION

SWITCH HARDWARE CONFIGURATION (Cont'd)

Entry

(1) All gain switches are enabled by the GAIN ENA PBI's.

(2) All FCS mode PBI's are independent, i.e., mixed modes are allowed. The GAIN ENA PBI's are independent.

(3) The gain switches are only enabled if the FCS mode is CSS. Thus, if both or either FCS axis mode PBI's is in AUTO, depressing either GAIN ENA modes that FCS axis to CSS and enables the gain switches in the selected axis. The other axis, if in AUTO, is not moded to CSS.

(4) Depressing a lighted CSS PBI restores the nominal gain structure in that axis and extinguishes the GAIN ENA lamp.

(5) The allowed mode combinations are shown in the following table:

Allowed Mode Combinations for Entry

	SWITCHES					
Allowed Combinations	PITCH GAIN ENA	ROLL/YAW GAIN ENA	PITCH CSS	ROLL/YAW CSS	PITCH AUTO	ROLL/YAW AUTO
					X	X
			X			X
				X	X	
			X	X		
	X		X	X		
		X	X	X		
	X	X	X	X		
	X		X			X
		X		X	X	

APPENDIX C

APPENDIX C

CPES CONFIGURATION

Vehicle:

North American Rockwell 140C Orbiter with first order, linear elevon, rudder, and speedbrake actuator models.

Vehicle mass properties as specified in June 1976 Flight Control Data Book.

Atmosphere:

1962 standard atmosphere

NASA turbulence model, NASA TMX-64589.

Aerodynamics:

EX Aero Data Tape #X17506 implemented on CPES on January 26, 1977. (SPS basic RCS aero interactions update completed October 31, 1977)

Aero variation combinations as listed in Appendix D with particular variation magnitudes as in the Orbiter June 1976 Aerodynamic Design Data Book, Volume 1.

Entry Flight Control System:

November 1976 FCS FSSR with approved CR updates 2425, 2166, 2243, 2422, and 2418.

Guidance:

New guidance update was completed in the CPES on October 10, 1977 to the November 1976 Entry Guidance FSSR Baseline. The nominal trajectory for this guidance model is the OFT-1 Reference Flight Profile, August, 1977.

Special Mods and Requirements:

- o New reconfiguration logic for activation of panel mounted gain switches by eyebrow panel PBI's;

  2 rate feedback switches (medium, low, and off positions)

  2 forward loop switches (high, normal, and low positions)

  Corresponding gain multipliers are enabled in the flight control system software with specified, addressable magnitudes.

- o RHC RCS "wrap-around" - activated/deactivated by pushbutton on RHC
  - Roll and pitch jets fired if RHC on hardstop of the respective axis.
  - Yaw jets fired incrementally, proportional to stick deflection out-of-detent in yaw.

- o "Default gains" as determined by $\bar{q}$ vs. velocity schedule for failed air data system

- o Compute RCS fuel consumption per maneuver

- o Bias the angle of attack being sent to the FCS

- o APU failures

- o Implement FCS mod to compensate automatically for an α bias

- o RCS jets failures

- o Simulate frozen surfaces as possibly caused by generic software failures. When software flag is set, do not execute flight control module, freeze surface commands. Begin executing flight control module again when the "BACKUP FCS" PBI is depressed.

- Capability to fix M, α, and $\overline{q}$ inputs to flight control at specified values.

AERODYNAMIC VARIATION COMBINATION CASES
(VALUES MODELED FROM JUNE 76 AERO DATA)

CASE NO.	MACH/ FLIGHT REGION	TYPE	AERODYNAMIC COMBINATIONS								
			C_m	C_{ℓ_β}	C_{n_β}	$C_{\ell_{\delta A}}$	$C_{n_{\delta A}}$	$C_{\ell_{\delta R}}$	$C_{n_{\delta R}}$	C_{y_β}	$C_{y_{\delta R}}$
1	M > 8	WOW Early FCS $C_{n_{\delta A}} < 0$ (Lateral trim problem with aileron)	−	+	+	−	+				
2	M > 5	BOB Early FCS	+	−	−	+	−				
3	M=8-5	WOW Early FCS $C_{n_{\delta A}} > 0$ (Lateral trim problem with aileron)	−	−	+	−	+				
4	M > 1.5	BOB Early FCS		−	+	+	+	+	−		
5	M=5-3	WOW Early FCS (Lateral trim problem with rudder - Low α)		+	+			+	+		
6	M=5-3	WOW Early FCS (Lateral trim problem with rudder - Low α)		+	+			(Correlated) −	+		
7	M=5-3	Max RCS usuage (Lateral trim problem with rudder - high α)		+	−			−	+		
8	M=3-1.5	C_{n_β} Dynamic (high α)		+	−	−	−				
9	M=5-1.5	Poor Dutch Roll Damping	+	+	−	−	−	−	+		
10	M=5-3	Two worst derivatives (Lateral trim problem with rudder - high α)	+		−				+		

APPENDIX D
AERODYNAMIC VARIATION COMBINATION CASES
(VALUES MODELED FROM JUNE 76 AERO DATA)

CASE NO.	MACH/ FLIGHT REGION	TYPE	AERODYNAMIC COMBINATIONS								
			C_m	C_{ℓ_β}	C_{n_β}	$C_{\ell_{\delta_A}}$	$C_{n_{\delta_A}}$	$C_{\ell_{\delta_R}}$	$C_{n_{\delta_R}}$	C_{y_β}	$C_{y_{\delta_R}}$
11	M=2-1	WOW Late FCS (Lateral-Directional controllability)	+	−	−	−	−	+ or − (Correlated)	+	+	−
12	M < 2	BOB Late FCS	−	−	+	+	+	+	−	−	+
13	M = .9	Ineffective Rudder at 0 speedbrake		+	−	−	−	−	+		−
14	M < 2	Requirement for Aileron to rudder interconnect schedule with α		−	−	+	+	−	−		
15	M=2-1	Two worst derivatives (Lateral-Directional Controllability)	+			−			+		
16	M=2-1	Two worst derivatives (Lateral-Directional Controllability)	+				−		+		
17	M < 2	WOW For large $(^{W\phi}/WD)^2$ (PIO Tendencies)	+	−	+	−	−	+	−	−	+
18	M=8-5	Max RCS usuage (Lateral trim problem with Aileron - high α)	−	−	−	−	+	−	+		

APPENDIX E

APPENDIX E
CPES RESET PARAMETERS

	RESET 01	RESET 03	RESET 13	RESET 15	RESET 17	
MACH	27.93	15.69	4.01	3.86	2.00	
α	39.83	39.86	17.08	17.08	11.15	(deg)
γ	-1.59	0.07	-3.29	-3.29	-5.79	(deg)
ϕ	0.03	-66.20	49.23	49.55	-7.83	(deg)
TAS	24370.85	16484.36	3984.09	3947.95	1946.95	(fps)
ψmag	33.17	68.63	80.20	80.20	68.69	(deg)
$\bar{q}$	0.04	78.80	222.53	95.05	238.52	(psf)
ALTITUDE (MSL)	365516.00	197224.0	102952.00	120679.00	71006.00	(ft)
ALTITUDE RATE	-675.46	20.36	-228.49	-226.55	-196.58	(fps)
IAS	3.49	152.40	256.11	167.38	265.15	(KEAS)
LATITUDE	28.58	35.42	34.84	34.83	34.74	(deg)
LONGITUDE	-172.74	-134.56	-119.76	-119.75	-118.72	(deg)

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