

SECTION 3

LEM PGNC SYSTEM DESCRIPTION

3.1 PGN

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

8/1 1966

Memo to Jim Nevins Room Ext.

For your review during the week of 5 Aug. 66

**Please communicate any errors or inconsistencies
to E. A. Olsson by 12:00 Noon, 5 Aug. 66**

from E. A. Olsson Room IL 7-389 Ext. 440

MURAN BOSTON

Power and Servo Assembly - LEM (PSA) ✓
LEM Signal Conditioner Assembly (SCA-FQ) ✓
LEM G&N Interconnect Harness Group ✓

3.2 PGNCS/Spacecraft Signal Interfaces

3.2.1 Interface Control Documents (ICD's)

Below are presented the Interface Control Documents (ICD's) which are pertinent to definition and understanding of the electrical/functional interfaces between PGNCS and the spacecraft and the astronauts. Additional existing ICD's pertaining to mechanical interfaces, thermal interfaces, etc, are not listed because they are not considered to be relevant to this document.

SECTION 3

LEM PGNC SYSTEM DESCRIPTION

3.1 PGNC Hardware Configuration

System 605 will be the PGNC system for Mission 278. It is a normal LEM system except for the Signal Conditioning Assembly which processes FLIGHT QUALIFICATION measurements as well as OPERATIONAL measurements. The Uplink Data link to the LGC will be operational for Mission 278, with no provision to block uplink. The system is comprised of the following major assemblies:

- Inertial Measurement Unit (IMU)
- Pulse Torque Assembly (PTA)
- Coupling Data Unit (CDU)
- LEM Navigation Base (NB)
- Alignment Optical Telescope (AOT)
- LEM Guidance Computer (LGC)
- Display Keyboard Assembly (DSKY)
- Computer Control and Reticle Dimmer Assembly (CCRD)
- Power and Servo Assembly - LEM (PSA)
- LEM Signal Conditioner Assembly (SCA-FQ)
- LEM G&N Interconnect Harness Group

3.2 PGNC/Spacecraft Signal Interfaces

3.2.1 Interface Control Documents (ICD's)

Below are presented the Interface Control Documents (ICD's) which are pertinent to definition and understanding of the electrical/functional interfaces between PGNC and the spacecraft and the astronauts. Additional existing ICD's pertaining to mechanical interfaces, thermal interfaces, etc, are not listed because they are not considered to be relevant to this document.

<u>General Inter- facing Area</u>	<u>ICD Title</u>	<u>ICD No.</u>	<u>Description</u>
PGNCS/LEM/AGS/ RR/LR FUNC- TION	LEM-PGNCS Func- tional Interface Requirements.	LIS-540-10001 (IRN's -1, -2, -3, -4, -5, -6, -7, -8)	A complete defini- tion of the functional interrelationships between the PGNCS, LEM(RCS, Descent Engine, Ascent Engine, AGS RR and LR)
	G&N Functional Flow Diagram	LID-540-10001 (Rev. A)	Schematic Drawing of G&N/LEM Inter- faces
TOTAL ATTITUDE/ ATTITUDE ERROR	LEM-PGNCS Electrical Interface for Total Attitude Sig- nals, Attitude Error Signals (Displays) and IMU Cage Signal (Com- mand)	LIS-350-10001 (Rev. A) (IRN-A-1)	Signal interface for: (a) SIN AIG * (b) COS AIG* (c) SIN AMG* (d) COS AMG* (e) SIN AOG* (f) COS AOG* (g) E_Y , PITCH ERROR* (h) E_Z , ROLL ERROR* (i) E_X , YAW ERROR* (j) IMU CAGE
	LEM-PGNCS 800 cps Excitation Signal, Electrical Interface	LIS-370-10007 (IRN-1)	Signal Interface for: (a) 800~ Reference
LGC/LEM	LGC-LEM Electrical Interface	LIS-370-10004 (Rev. B)	Signal interface and electric loads for complete LGC/LEM interface. For sig- nal list (see also sec. 3.2.2)

* 800 cps modulated signals.

<u>General Inter- facing Area</u>	<u>ICD Title</u>	<u>ICD No.</u>	<u>Description</u>
PGNCS/AGS	Abort Guidance Sec. - tion Electrical Inter- face with PGNCS	LIS-300-10002 (IRN-1)	Signal interface for: (a) CDU Zero Signal (b) Incremental Total Attitude: $+\Delta AIG$ (c) Incremental Total Attitude: $-\Delta AIG$ (d) Incremental Total Attitude: $+\Delta AMG$ (e) Incremental Total Attitude: $-\Delta AMG$ (f) Incremental Total Attitude: $+\Delta AOG$ (g) Incremental Total Attitude: $-\Delta AOG$ (Also see sec. 3.2.2)
PGNCS/RENDEZ- VOUS RADAR	PGNCS to Rendez- vous Radar Angle	LIS-370-10006 (IRN's -1, -2, -3)	Signal interface for: (a) Sine Shaft 1X * (b) Cos Shaft 1X * (c) Sine Shaft 16X * (d) Cos Shaft 16X * (e) Sine Trunnion 1X * (f) Cos Trunnion 1X * (g) Sine Trunnion 16X * (h) Cos Trunnion 16X * (i) Shaft axis angular designate * (j) Trunnion axis an- gular designate *
PGNCS/TELEMETRY LEM PGNCS Meas- urement Interface Provisions		LIS-370-10003 (IRN's -1, -2, -3, -4)	Signal interface for all G&N PCM and DFI measurements.
PGNCS/LEM DISPLAY	LEM-PGNCS Later- al and Forward Vel- ocity Electrical Inter- face (DISPLAYS)	LIS-350-10002 (IRN-1)	Signal Interface for: (a) V_Z - Forward vel- ocity + (b) V_Y - Lateral vel- ocity + (Not used on Mission 278)

* 200 cps modulated signals
+ d-c signals

<u>General Inter- facing Area</u>	<u>ICD Title</u>	<u>ICD No.</u>	<u>Description</u>
PGNCS/LEM POWER	PGNCS Prime Power Requirements and Characteristics	LIS-390-10002 (IRN-1)	Total AC and DC Power specification from LEM for G&N
S-Band Steerable Antenna/PGNCS	S-Band Steerable* Antenna Functional Interface with PGNCS	LIS-380-10001 (IRN-1)	Defines LGC Display requirements with regards pointing the S-Band Antenna

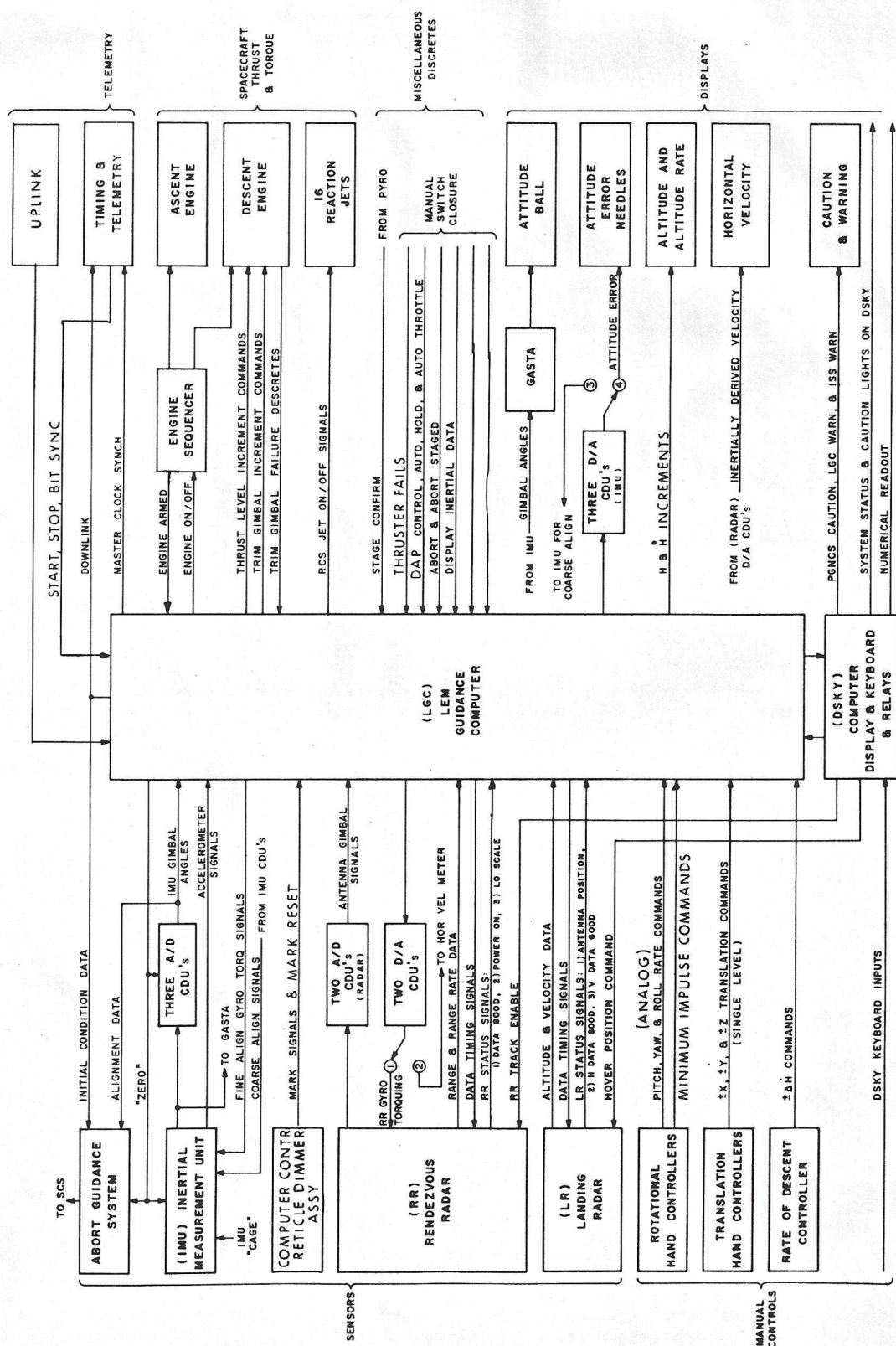
3.2.2 LGC/LEM Signal Interface

The following section lists the complete signal interface between the LGC and the LEM as described in detail in ICD LIS-370-10004B. Figure 3-1 presents a schematic representation of the interface.

3.2.2.1 LGC/LEM Interface - Inputs to LGC

- | | |
|----------------------------------|-----------------|
| (1) Automatic Mode | |
| (2) Attitude Hold Mode | |
| (3) Out of Detent | |
| (4) Start "Abort" Program | |
| (5) Start "Abort Stage" Program | |
| (6) Engine Armed | |
| (7) Digital Autopilot in Control | |
| (8) In Auto Throttle | |
| (9) Display Inertial Data* | CONTROL MODE |
| (10) Rate of Descent Bar* | AND STATUS |
| (11) Rate of Descent - plus * | SIGNALS |
| (12) Rate of Descent - minus* | |
| (13) Thruster 2-4 Fail | |
| (14) Thruster 5-8 Fail | |
| (15) Thruster 1-3 Fail | |
| (16) Thruster 6-7 Fail | |
| (17) Thruster 14-16 Fail | |
| (18) Thruster 13-15 Fail | |
| (19) Thruster 9-12 Fail | |
| (20) Thruster 10-11 Fail | |
| (21) Stage Verified | |
| (22) +X Translation Command | TRANSLATION |
| (23) -X Translation Command | HAND CONTROLLER |

* Not used on Mission 278



(24) +Y Translation Command	TRANSLATION
(25) -Y Translation Command	HAND CONTROLLER
(26) +Z Translation Command	
(27) -Z Translation Command	
(28) Pitch Rate Command	ATTITUDE HAND CONTROLLER (800 cps modulated signals)
(29) Roll Rate Command	
(30) Yaw Rate Command	
(31) Pitch Gimbal Off	DESCENT ENGINE
(32) Yaw Gimbal Off	
(33) RR in "1" (Data Flow)	RENDEZVOUS RADAR
(34) RR in "0" (Data Flow)	
(35) RR Data Good	
(36) RR Power On and Auto Mode	
(37) RR Range Low Scale	LANDING RADAR
(38) LR in "1" (Data Flow)	
(39) LR in "0" (Data Flow)	
(40) LR Range Data Good	
(41) LR Velocity Data Good	
(42) LR Position #1 Indication	
(43) LR Position #2 Indication	
(44) LR Range Low Scale Factor	UPLINK
(45) Uplink Data (Binary "1")	
(46) Uplink Data (Binary "0")	DOWNLINK
(47) Start Pulse	
(48) Stop Pulse	
(49) Bit Sync Pulse	MINIMUM INPUT CONTROLLER
(50) Plus Roll Impulse	
(51) Minus Roll Impulse	
(52) Plus Pitch Impulse	
(53) Minus Pitch Impulse	
(54) Plus Yaw Impulse	
(55) Minus Yaw Impulse	

3.2.2.2 LGC/LEM Interface - Output from LGC

(1) Increase Throttle	DESCENT ENGINE
(2) Decrease Throttle	
(3) + Pitch Trim	
(4) - Pitch Trim	
(5) + Roll Trim	
(6) - Roll Trim	

(7) Engine On	}	ENGINE SEQUENCER (DESCENT AND ASCENT)
(8) Engine Off		
(9) RCS Jet #2 (+X)	}	RCS JET DISCRETES
(10) RCS Jet #6 (+X)		
(11) RCS Jet #10 (+X)		
(12) RCS Jet #14 (+X)		
(13) RCS Jet #5 (-X)		
(14) RCS Jet #9 (-X)		
(15) RCS Jet #1 (-X)		
(16) RCS Jet #13 (-X)		
(17) RCS Jet #12 (+Y)		
(18) RCS Jet #16 (+Y)		
(19) RCS Jet #4 (-Y)		
(20) RCS Jet #8 (-Y)		
(21) RCS Jet #11 (+Z)		
(22) RCS Jet #7 (+Z)		
(23) RCS Jet #3 (-Z)		
(24) RCS Jet #15 (-Z)		
(25) RR Reset Strobe	}	RENDEZVOUS RADAR
(26) RR Range Gate Strobe		
(27) RR Range Rate Gate Strobe		
(28) RR Counter Readout Command		
(29) Auto Angle Track Enable	}	LANDING RADAR
(30) LR Reset Strobe		
(31) LR Range Gate Strobe		
(32) LR X _A Velocity Gate Strobe		
(33) LR Y _A Velocity Gate Strobe		
(34) LR Z _A Velocity Gate Strobe		
(35) LR Counter Readout Command		
(36) LR Antenna Position Command	}	DOWNLINK and TIMING
(37) Serial Digital Data *		
(38) Sync Signal - 1024 KC	}	CAUTION and WARNING SIGNALS (see also para. 3. 2.3)
(39) LGC (warning)		
(40) PGNCS (Caution)		
(41) Inertial Reference (Warning)	}	ALTITUDE AND ALTITUDE RATE METERS
(42) Altitude "0"		
(43) Altitude "1"		
(44) Altitude Rate "0"		
(45) Altitude Rate "1"		

* Also to AGS for initialization

3.2.3 PGNCS Failure Monitor

The PGNCS performance and operational readiness are self-monitored and caution and warning information are displayed to the crew. Two warning (red) lamps are actuated by the PGNCS on the Caution/Warning Panel: LGC Warning indicates computer failure; INERTIAL REFERENCE warning indicates failure of the inertial subsystem. Also a PGNCS Caution (amber) lamp is actuated to indicate non-critical problems in the system. Further detail regarding the caution items is displayed by means of the DSKY event lamps and the DSKY data registers (in the event of a program alarm.) The failure monitor mechanization is shown in Figure 3-2.

3.2.3.1 LGC Warning

An LGC warning alarm is generated in the event of LGC power failure, scaler failure of either of two types, restart or counter fail during LGC operate, or in response to an alarm test program. As is shown in Figure 3-2 a scaler fail or prime power fail result in immediate alarm indication whereas the other inputs are buffered by a filter so as to prevent momentary transient disturbances which recover from causing a warning alarm. In this subsection the various inputs and conditions associated with LGC warning are defined.

- (a) SCAFAL - Occurs if scaler stage 17 (1.28 sec period) fails to produce pulses. This provides a check on the timing for all logic alarms.
- (b) COUNTER FAIL - Occurs if counter increments happen too frequently or else fail to happen following an increment request. "Too frequently" means continuous counter requests and/or incrementing for from .625 ms to 1.875 ms.
- (c) SCADBL - Occurs if the 100 pps scaler stage operates at a pulse rate of 200 pps or more.
- (d) PARITY FAIL - Occurs if any accessed word in fixed or erasable memory whose address is octal 10 or greater contains an even number of "ones".
- (e) RUPT LOCK - Occurs if interrupt is either too long or too infrequent. The criterion for "too long" is phase dependent varying from 140 ms to 300 ms. Likewise the criterion for "too infrequent" varies from 140 ms to 300 ms.

- (f) TC TRAP - Occurs if too many consecutive TC or TCF instructions are run or TCF instructions are too infrequent. The criterion for "too many" varies from 5 ms to 15 ms duration. The criterion for "too infrequent" varies from 5 ms to 15 ms absence.
- (g) NIGHT WATCHMAN- Occurs if the computer should fail to access address 67 within a period whose duration varies from .64 sec to 1.92 sec.
- (h) V FAIL - Occurs if the LGC voltages (28, 14, 4) are out of limits. This signal produces STRT1 if it stays on for a period of between 157 and 470 μ sec. If the computer is in the STANDBY mode, an input to the LGC WARNING FILTER is generated simultaneous with STRT1. The following criteria apply for V FAIL:

4 V Supply > 4.4V	14 V Supply > 16V
4 V Supply < 3.65V	14 V Supply < 12.5V
	28 V Supply < ~22.6V
- (i) STANDBY - This is a signal which turns on RESTART and turns off the switchable +4 and +14 voltage, thus putting the LGC into a low power mode where only the scaler, timing signal, and a few auxiliary signals are operative. STANDBY is initiated by first setting the ENABLE STANDBY outbit (CH13 B11), and then pressing the STANDBY button on the DSKY for a time which varies from .64 sec to 1.92 sec, at the end of which time the STANDBY LIGHT is turned on. (All LGC alarms are inhibited during the standby mode with the exception of LGC WARNING, which can be caused by VOLTAGE FAIL or SCALER FAIL; and TEMPERATURE CAUTION, which can be caused by TEMP ALARM.) Normal operation is resumed by pressing the STAND - BY button on the DSKY again, time of depression same as above.
- (j) RESTART - RESTART occurs at next time 12 following occurrence of any one or more of the parameters shown in Figure 3-2 except OSCILLATOR FAIL.

RESTART occurs immediately and forces time counter to 12 upon occurrence of OSCILLATOR FAIL. (See paragraph "1" below.)

RESTART causes the computer to transfer control to address 4000 as soon as it disappears. It sets a flip-flop which lights the RESTART CAUTION lamp in the DSKY.

The Flip-flop is reset either by the ALARM RESET hard wired signal or by the CAUTION RESET outbit CH11 B10. ALARM TEST operates the lamp but not the flip-flop.

- (k) WARNING FILTER - This circuit is used to operate the LGC WARNING output following repeated or prolonged occurrences of the parameters shown in Figure 3-2. All occurrences of these signals are stretched so that no more than one input to the filter is generated in each 160 millisecond period. Approximately six consecutive stretched pulses cause LGC WARNING to turn on for about 5 seconds. Non-consecutive stretched pulses may also cause LGC WARNING after an interval dependent on the frequency of the pulses. The output will not occur if input pulses occur at a frequency of less than 0.9 pps; and the output will remain on if pulses occur at a frequency of 0.6 pps or more. The threshold of the filter resumes its normal level with a time constant of many seconds after the filter has received inputs. An immediate reset of the LGC FAIL due to a WARNING FILTER output is therefore not possible.
- (l) OSCILLATOR FAIL - Occurs if the oscillator stops. Has nominal 250-millisecond delay to keep signal present after the oscillator starts. Also occurs when LGC is in STANDBY because of loss of power to front end of circuit. This give 250-millisecond delay in starting when LGC comes out of STANDBY into OPERATE. Causes immediate restart without waiting for time pulse 12.

3.2.3.2 Inertial Reference Warning

The Inertial Reference Warning signal is the logical "OR" of the following parameters, any one of which will cause an Inertial Reference Warning under the following conditions:

(a) IMU Fail

- (1) IG Servo Error - greater than 2.9 mr for 2 sec
- (2) MG Servo Error - greater than 2.9 mr for 2 sec
- (3) OG Servo Error - greater than 2.9 mr for 2 sec
- (4) 3200 cps - decrease to 50% of normal level
- (5) 800 wheel supply - decrease to 50% of normal level

These parameters are generated in the Inertial Subsystem. However, the "FAIL" signal itself is under LGC program control. It is ignored by the LGC program when the G&N System is in the

Coarse Align Mode and during the 5 second interval following Coarse Align. During this mode the servo errors normally exceed the above criteria.

(b) PIPA FAIL

Occurs if no pulses arrive from a PIPA during a 312.5 μ sec period, or else if both plus and minus pulses occur, or if a "long time" elapses without at least one plus pulse and at least one minus pulse arriving. By "long time" is meant a period of between 1.28 sec and 3.84 sec.

This FAIL signal is generated totally within the LGC and thus is completely under LGC program control. Its generation is enabled by the LGC only during LGC controlled translation or thrusting maneuvers.

(c) ISS CDU FAIL (Monitored for each of 3 CDU's)

- (1) CDU fine error - in excess of 1.0V rms
- (2) CDU coarse error - in excess of 2.5V rms
- (3) READ COUNTER limit cycle - in excess of 160 cps
- (4) $\cos(\theta - \phi)$ - below 2.0V
- (5) +14 DC Supply - decrease to 50% of normal level

These parameters are generated in the Inertial Sub System. However, the "FAIL" signal itself is under LGC program control. It is ignored by the LGC program when the G&N System is in the CDU Zero Mode. During this Mode the CDU errors normally exceed the above criteria.

3.2.3.3 PGNCS Caution

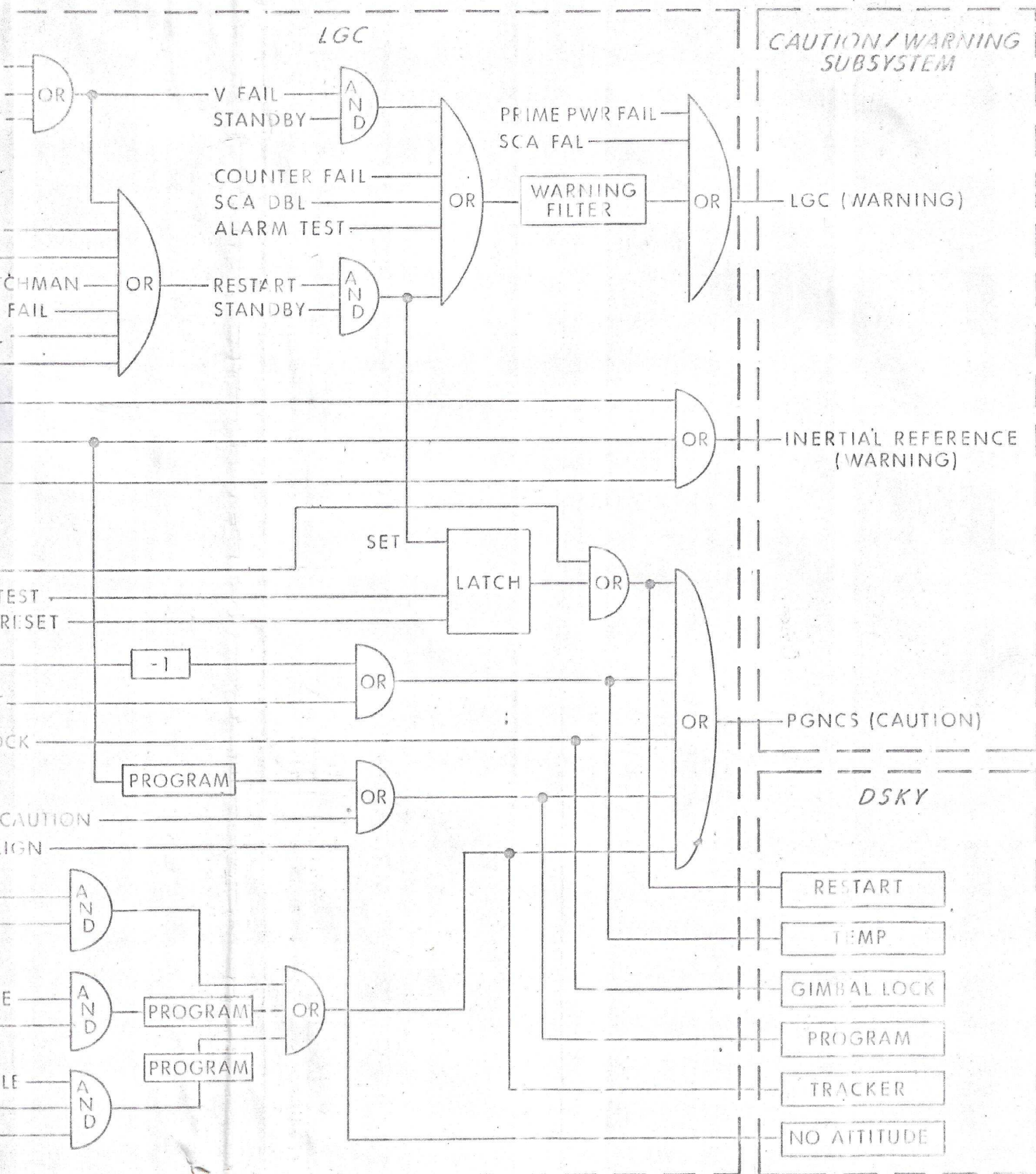
The PGNCS Caution lamp is actuated by the following undesirable but non-critical events:

- (a) LGC Restart during Operation. In the event of Restart during operate a latch is set in the LGC which maintains the PGNCS Caution alarm and the RESTART lamp on the DSKY until the latch is reset by program or until the latch is manually reset by ALARM RESET. For further detail see section 3.2.3.4
- (b) Temperature out of Limits. The LGC receives a signal from the IMU when the stable member temperature is in the range 126.3°F to 134.3°F. In the absence of this signal, the Caution alarm and the TEMP lamp on the DSKY are actuated.

- (c) Gimbal Lock. When the LGC determines that the middle gimbal angle (MGA) of the IMU is greater than 70° , the Caution alarm and the Gimbal Lock lamp on the DSKY are actuated. When MGA exceeds 85° the ISS is downmoded to Coarse Align and the No Attitude lamp on the DSKY is actuated.
- (d) Program Alarm. Under a variety of situations a program alarm is generated. Figure 3-2 illustrates one example, that of PIPA fail when the vehicle is not in a thrusting mode. Under program control the LGC inhibits this alarm for 10 sec after system turn-on. The program alarm actuates the Caution alarm and the Program lamp on the DSKY. For further information see section 3.2.3.4.
- (e) Tracker Alarm. When the Rendezvous Radar or Landing Radar are in use the Caution alarm and Tracker lamp on the DSKY will be energized by any of the following three occurrences:
 - (1) RDR CDU Fail (Monitored for both CDU's) defined by same failure modes with same constraints as IMU CDU Fail [see section 3.2.3.2 (c)] . This fail signal is generated in the CDU and, under program control, generates a Caution alarm only when the PGNCS is in the RDR Auto mode.
 - (2) RR Fail Defined by presence of the Rendezvous Radar Data Good Bar discrete during a data read sequence by the LGC or inability of LGC to successfully get coherent data.
 - (3) Landing Radar Altitude Data Good Bar or Velocity Data Good Bar when the PGNCS is in the LRDR enable mode and when the LGC is attempting to get data from the LRDR or anytime when the LGC is attempting unsuccessfully to get data, the Caution alarm and Tracker lamp on the DSKY are actuated.

3.2.3.4 Restart and Program Alarms

When the Restart or Program Alarm lamps are illuminated on the DSKY, either V 05 N 31 will automatically appear on the DSKY with a key to the source of the alarm displayed in R1 or by astronaut call up from the DSKY this information can be made available. This allows the astronaut to identify and normally correct the alarm condition. The listing of program alarms is included in Section 4.



3-3

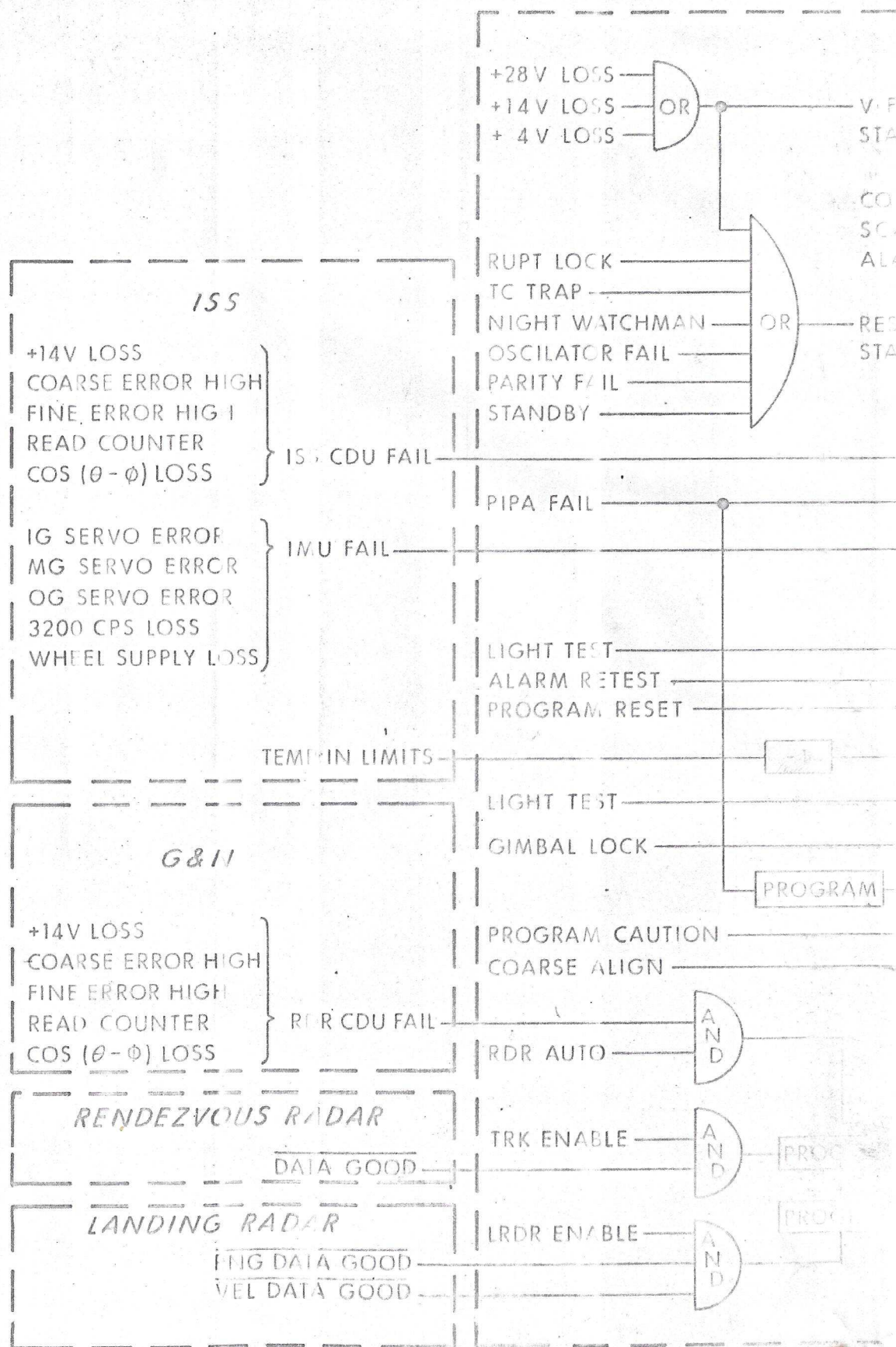


Fig. 3-2 PGNCS Failure Monitor

pulses cause LGC WARNING to turn on for about 5 seconds. Non-consecutive stretched pulses may also cause LGC WARNING after an interval dependent on the frequency of the pulses. The output will not occur if input pulses occur at a frequency of less than 0.9 pps; and the output will remain on if pulses occur at a frequency of 0.6 pps or more. The threshold of the filter resumes its normal level with a time constant of many seconds after the filter has received inputs. An immediate reset of the PGNCS FAIL due to a WARNING FILTER output is therefore not possible.

(1) OSCILLATOR FAIL - Occurs if the oscillator stops. Has nominal 250-millisecond delay to keep signal present after the oscillator starts. Also occurs when AGS is in STANDBY because of loss of power to front end of circuit. This gives 250-millisecond delay in starting when AGC comes out of STANDBY into OPERATE. Causes immediate restart without waiting for time pulse 12.

3.3 LEM Digital Autopilot

3.3.1 Introduction

The LEM digital autopilot (DAP) has interfaces with 16 RCS solenoid driver pre-amplifiers and the pitch and roll trim gimbal servo drives. During descent engine burning the DAP tries to control the spacecraft attitude with the trim gimbal servo in order to save RCS propellants; but if the rather slow trim gimbal drive does not keep the attitude error within certain bounds, the RCS jets are used until the error is brought within the attitude deadband and then control is returned to the trim gimbal servo.

The DAP works either in conjunction with a PGNCs guidance loop to provide an integrated guidance and control system, or in conjunction with the translational hand controller and the rotational hand controller. In the latter mode of operation the DAP provides the astronaut with an integrated translation and rate-command/attitude-hold stabilization and control system.

The DAP monitors the 8 RCS thruster-off signals (Bits 1 through 8 of LGC inbits channel 32) and chooses the best set of jets to use under the combined conditions of rotational commands, translational commands, and disabled jets.

Propellant economy, minimization of the number of RCS jet firings, operation with detected and undetected jet failures, and compliance with the data and requirements of the LEM PGNCs Equipment Performance and Interface Specification, have provided the design criteria for the LEM DAP.

3.3.2 Data Requirements for the LEM DAP

In order to meet the design criteria outlined above and exploit contemporary optimization control techniques, the LEM DAP uses a dynamic model of the LEM spacecraft. For each flight the following data is required:

1. Complete moment of inertia history of the spacecraft.
2. Complete I_{SP} history of the main propulsion systems.
3. The torque of each RCS control jet.
4. Complete history of the distance between the point of application of the main propulsion system's thrust vector and the c.g. of the spacecraft.
5. The amplitude and frequency of the vibration at the IMU station.
6. The rate of change of the pitch and roll trim gimbal angle (descent propulsion system).
7. Complete time history of the nominal disturbing torque due to the main engine's thrust vector not passing through the c.g. of the spacecraft. (ascent propulsion system).

8. Bending mode data and slosh mode data when the LEM is coupled to the CSM and SPS backup must be performed.

The above data should be available and validated upon approval of the GSOP.

3.3.3 Selectable Modes in the Autopilot

By means of the LGC keyboard and the Mode Select switch, the astronaut can select any of the following modes. (For all of these modes, except the last, the Guidance Select switch must be in the PGNCS position, not the AGS position.)

Mode	Mode Select Switch Position	DSKY Entry
Minimum Impulse	Attitude Hold	Verb 73
Rate Command/Attitude Hold	Attitude Hold	Verb 74
Automatic	Auto	None Required
X-Axis Over-ride*	Auto	None Required
OFF	OFF	None Required

The Minimum Impulse mode is used by the astronaut to control the spacecraft with very low rate maneuvers. Each discrete deflection of the RHC 2.5 degrees or more out of detent will cause the DAP to issue commands to the appropriate jets for a minimum impulse. In this mode the astronaut must do his own rate damping, his own attitude steering, his own anticipation, etc. This mode does not physically require the IMU to be running; but it is programmed so that it is logically necessary for the IMU to be running and available for DAP use.

The astronaut can enter the Minimum Impulse mode by entering Verb 73 on the DSKY. He can then perform an economic low rate maneuver to a new orientation of the spacecraft. By entering Verb 74 on acquiring the new attitude and releasing the RHC to the in-detent position, the astronaut can place the DAP back in attitude hold and the digital autopilot will cause the vehicle to limit cycle with the normal attitude steering minimum impulses about the new orientation. This feature is attained by execution of a program on a Verb 74 entry which places the contents of the CDU registers into the CDU desired

*Not available during LPD use.

registers and changes the DAP mode of operation. This mode should be useful when the RCS propellant supply is low and the time line permits the attitude maneuvers to be performed at low rates.

A few words are in order about the operation of the rotational hand controller during the minimum impulse mode. The LGC commands one minimum impulse for each excursion of the hand controller beyond the limit switches (they are mounted 2.5 degrees to each and every side of the in-detent position). The RHC must be returned momentarily to the in-detent position between each pair of minimum impulses. Thus, no more than one pulse will be commanded by the LGC for each deflection of the hand controller. The maximum frequency at which minimum impulses can be commanded is about 5 per second; but it would be wasteful to operate the minimum impulse mode at such a high frequency. If the astronaut wants a moderate change in rate rather than a very small one, he should use the rate command mode.

The rate command/attitude hold mode is the normal means of astronaut control of the spacecraft. The maximum maneuver rate about any axis of the spacecraft is 20° /second. The RHC acts as an analog device during rate command, producing a voltage proportional to stick deflection. The voltage represents commanded rate; it is converted to a binary number (quantized at about 0.625 deg/sec per bit) and presented to the DAP. When the stick is out of detent the DAP tries to make the vehicle rate match the rate commanded by the hand controller. When the rate error is less than the rate deadband (0.4 deg/sec during descent, 1.0 deg/sec during ascent) the jets are no longer commanded on. But if the rate error exceeds a certain bound (2.0 deg/sec in ascent, 1.4 deg/sec in descent) four jets are used to torque the spacecraft. When the RHC is returned to the in-detent position, the DAP computes the time of jet burning required to zero the vehicle's rates. When the vehicle's rate is brought inside a deadband about zero rate, the contents of the CDU registers are transferred to the CDU desired registers and attitude steering about the vehicle's newly attained position is commenced. If the spacecraft has a sizable pitch and roll rate error, diagonal jets are used, an efficient selection of jets.

The astronaut has his choice of two attitude deadbands during attitude hold. He enters Verb 75 for the wide deadband, 5.0 degrees, or Verb 76 for the narrow deadband, 0.3 degrees.

The auto mode is used when the primary guidance system rather than the astronaut is commanding the orientation of the spacecraft. The guidance equations and steering laws communicate with the DAP by periodically placing

new numbers in the CDU desired registers and by specifying appropriate attitude deadbands. The DAP really performs no differently in Attitude Hold and Automatic. The source of the numbers in the CDU desired registers is different during Attitude Hold and Auto, but the DAP is programmed to be independent of this source.

3.3.4 Rate Command Equations

The implementation of the rate command mode is conveniently described by introducing the concept of an urgency function. The urgency function concept is central to the implementation of the attitude steering mode also.

The urgency function yields a number which gives a measure of urgency to rotate about a given axis of the spacecraft. Consider the pitch-roll problem. Each RCS jet which is oriented parallel to the LEM X-axis can both pitch (Q) and roll (R). Thus, the jets can pitch the spacecraft, roll it, or torque it about some intermediate axis. Indeed, there is a ray of axes perpendicular to the LEM X-axis about which torque can be applied. These rays are separated by 45° ; and thus, if one could define an optimum axis to torque about, this optimum axis would never be further than 22.5° from an actual torque axis. Furthermore, if one could select at the outset the best (or a very good) axis to rotate about, the jet selection problem would be partially solved and the time of jet torquing would be a single axis calculation.

The definition of an urgency function for the rate command problem is particularly easy.

$$U_R = \Delta\omega_R = \omega_R - \omega_{RD}$$

$$U_Q = \Delta\omega_Q = \omega_Q - \omega_{RD}$$

where the subscript D refers to the commanded or desired body rates. Having defined the urgency functions we can define an urgency plane. This plane, shown in Fig. 3-3, permits the decision of which axis to torque about and (if there is a choice possible) how many jets to use. Thus, once the urgency plane is divided into regions as the plane in Fig. 3-3 is divided, the urgency plane becomes a decision plane.

One of the important features of the urgency plane approach is that the Pitch-Roll problem is turned into a single axis problem. Indeed, the yaw problem (P-axis) is the same as the pitch only or roll only problem.

Figure 3-4 shows a flow graph for the processing of the Q-R rate command or attitude hold problem.

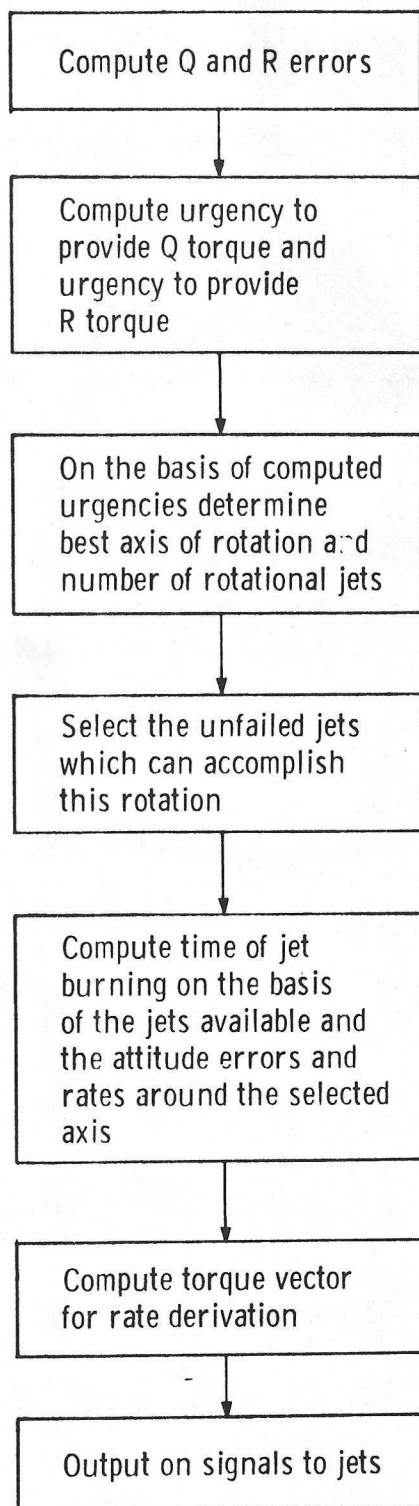


Fig. 3-4 Logical Flow for Jet-On Time

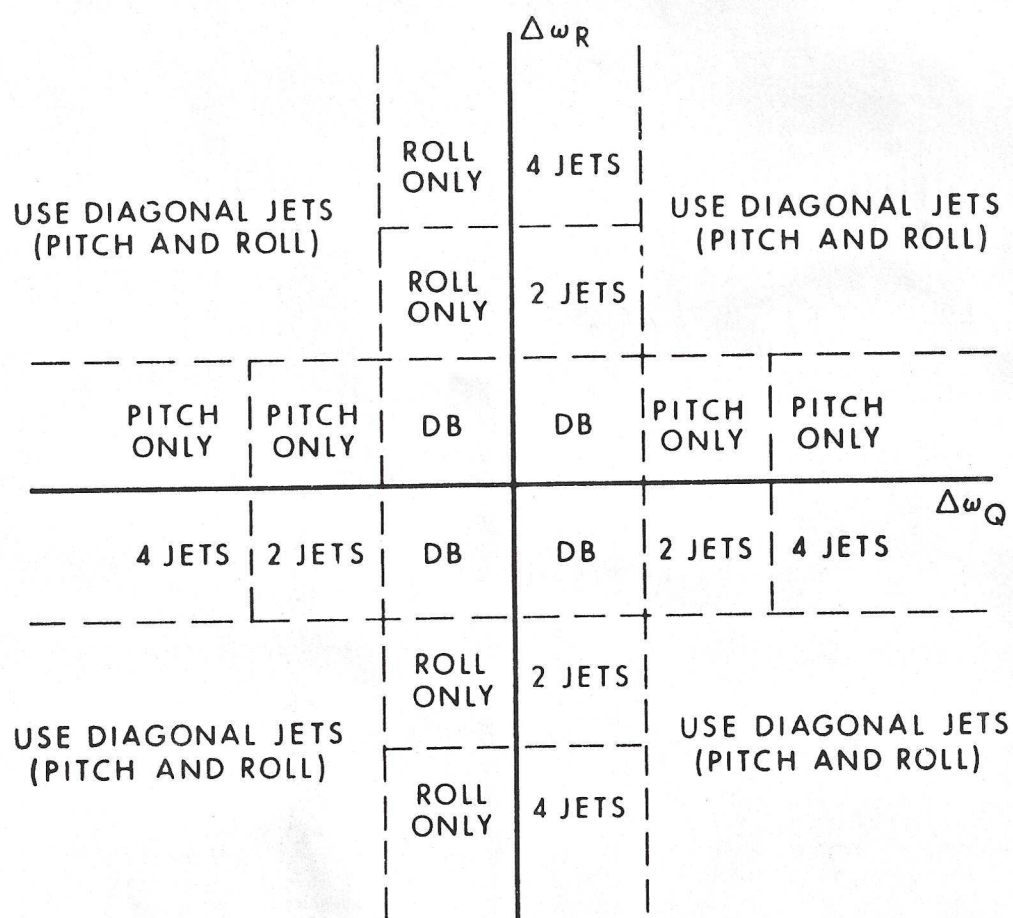


Fig. 3-3 Rate Command Pitch-Roll Urgency Plane

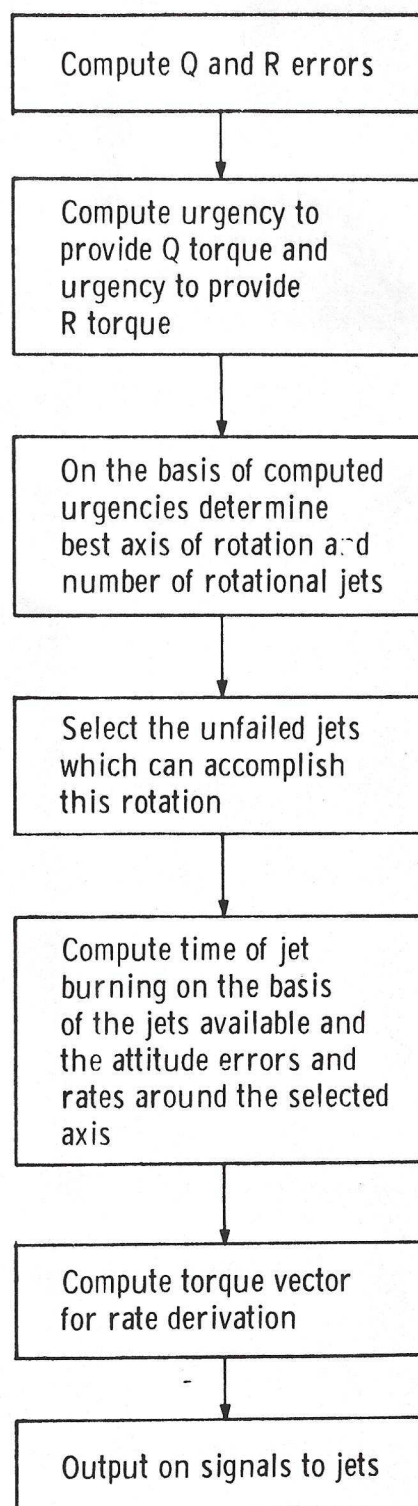


Fig. 3-4 Logical Flow for Jet-On Time

After the axis of rotation has been selected and the actual number of torquing jets discovered, the time of jet thrusting is computed. This time is computed by dividing the rate error around the selected axis by the jet acceleration around that axis.

$$T_{JET} = \Delta\omega/a$$

3.3.5 Attitude Steering Equations (Descent and Drifting Flight)

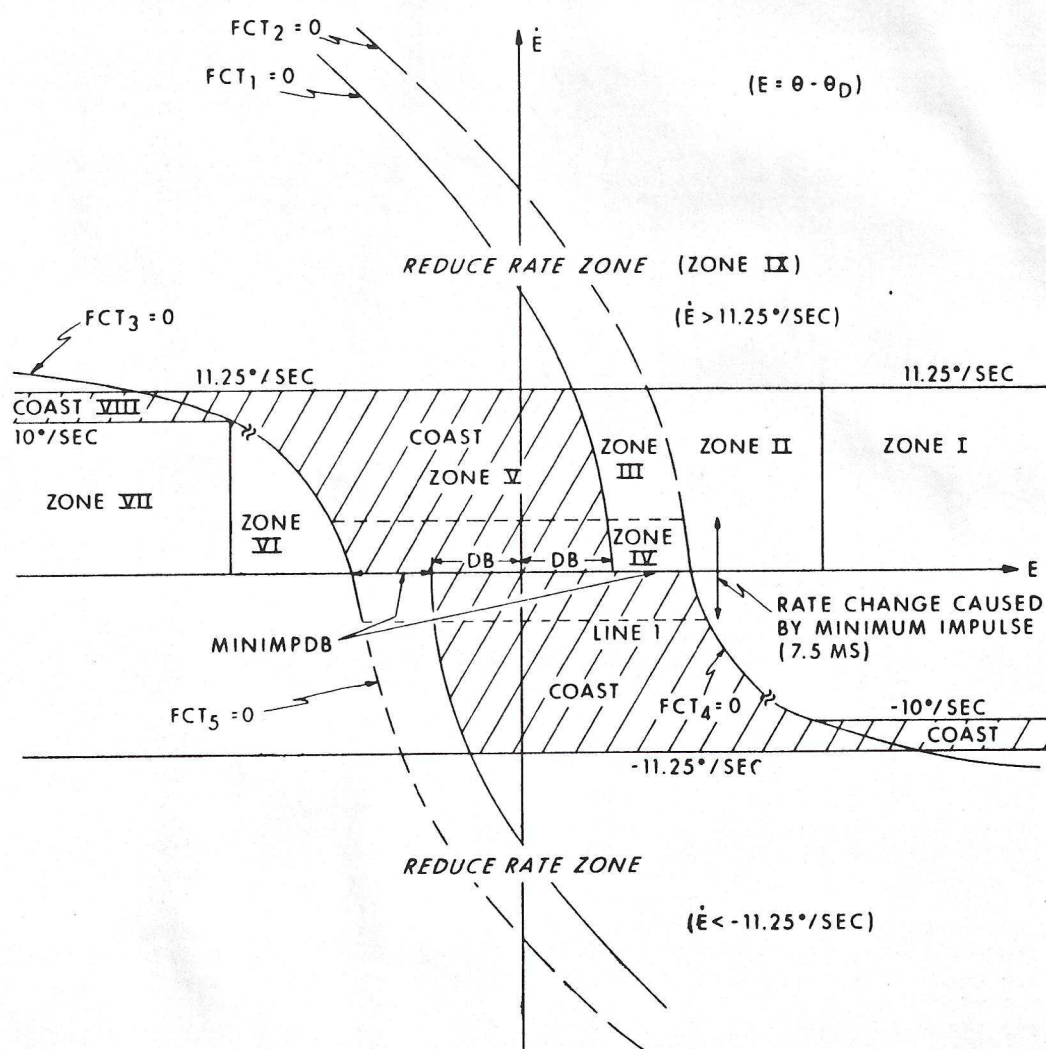
During descent engine burning there are in effect two parallel control systems, the RCS jets and the trim gimbal. The yaw control problem is always handled by RCS jets; but the pitch-roll problem is handled by the trim gimbal when the trim gimbal drive can function fast enough to keep the attitude errors tolerable. It is the RCS jet control equations which are described in this section. These equations are used for drifting flight as well as descent engine burning, in other words, whenever the disturbing acceleration due to the main engine is either non-existent or maintained at a small value by the trim gimbal.

The phase plane considerations which permit the calculation of a T_{jet} time are illustrated in Fig. 3-5. The jet-off or coast region has a rather peculiar shape. This shape has been chosen on the basis of theoretical investigations and empirical observations. This shape gives an adequate transient response and good propellant economy. For example, the offset of the coast region below the E-axis gives rise to zones III and IV in which there is a high probability of entering a minimum impulse limit cycle. The width of zone IV is about 0.3 degree or greater. The acquisition of a minimum impulse limit cycle is considerably enhanced by the existence of regions III and IV.

The RCS jet torquing time is computed by calculating the rate and attitude errors, deciding how many jets will be used, and then computing the time required to drive to the boundary of the coast region. If the vehicle is already in the coast region, T_{jet} is zero and is not calculated.

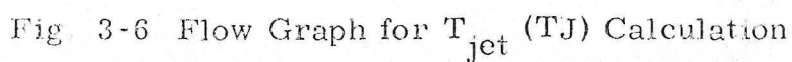
Figure 3-6 is a flow graph of the T_{jet} calculation. Figure 3-7 is a graph of parabola $FCT_3 = 0$. This graph illustrates the magnitude of rate which is used to null a given magnitude of attitude error. Figure 3-6 illustrates that T_{jet} is calculated by (1) testing to see what zone the phase point is in and (2) calculating the time required to torque to the boundary of the coast region. The nomenclature of the flow graph is:

- TJ = calculated jet on time (time required to torque to boundary of coast region)
- $T_{(\dot{E} - 0)}$ = time required to torque to the E axis (i. e. to $\dot{E} = 0$)
- $T_{(0 - \dot{E}_F)}$ = time required to torque from the E axis to the boundary of the coast region



In Zones I-IV, negative torque is applied i.e. $\ddot{E} < 0$.
 In Zones VII and VIII, positive torque is applied i.e. $\ddot{E} > 0$.

Fig. 3-5 Phase Plane Depiction of T_{jet} Calculation



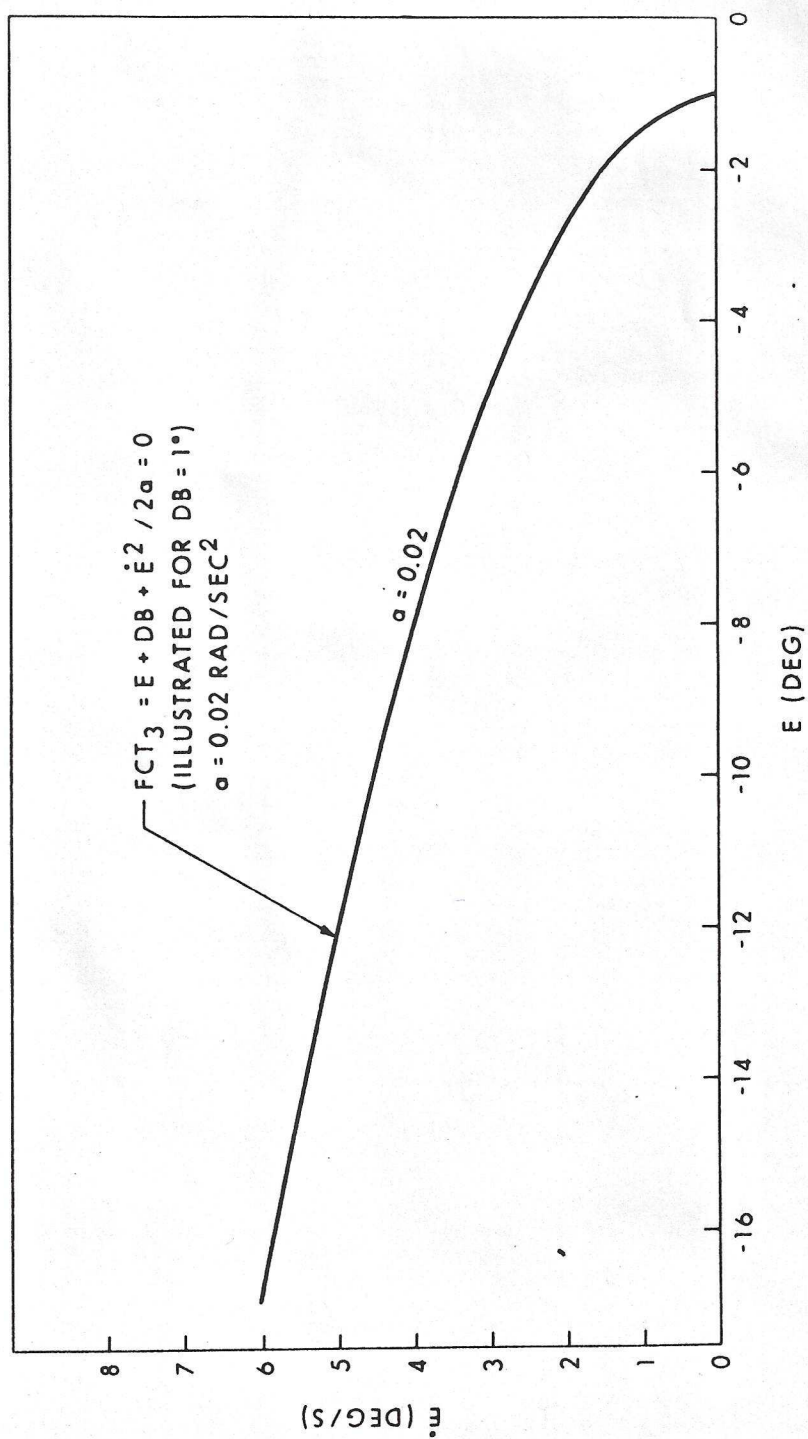


Fig. 3-7 Graph of $FCT_3 = 0$

The computation of the TJ is simplified by reflecting the problem into the positive \dot{E} half of the phase plane if \dot{E} is negative. Simultaneous reference to Fig. 3-5 and Fig. 3-6 should make the calculation of TJ self-explanatory. If the principles of a phase plane representation of the attitude control problem are unfamiliar to the reader he may refer to MIT Apollo Report, R-499, Design Principles of the Lunar Excursion Module Digital Autopilot. (R-499 is not correct in detailed explanations of the actual LEM DAP mechanization but the discussions of the physical principles have tutorial value).

Urgency functions are applied to the Pitch-Roll (Q-R) attitude control problem to determine which axis to rotate about. The concept of an urgency function for the Pitch-Roll attitude control problem is completely analogous to this concept for the Pitch-Roll rate command problem. The implementation is more difficult because the attitude error around a given axis as well as the rate about the axis determine the urgency to apply control torque around that axis. The same advantages are gained by applying this concept to the Pitch-Roll attitude steering problem: the two axis problem is transformed into a single axis problem.

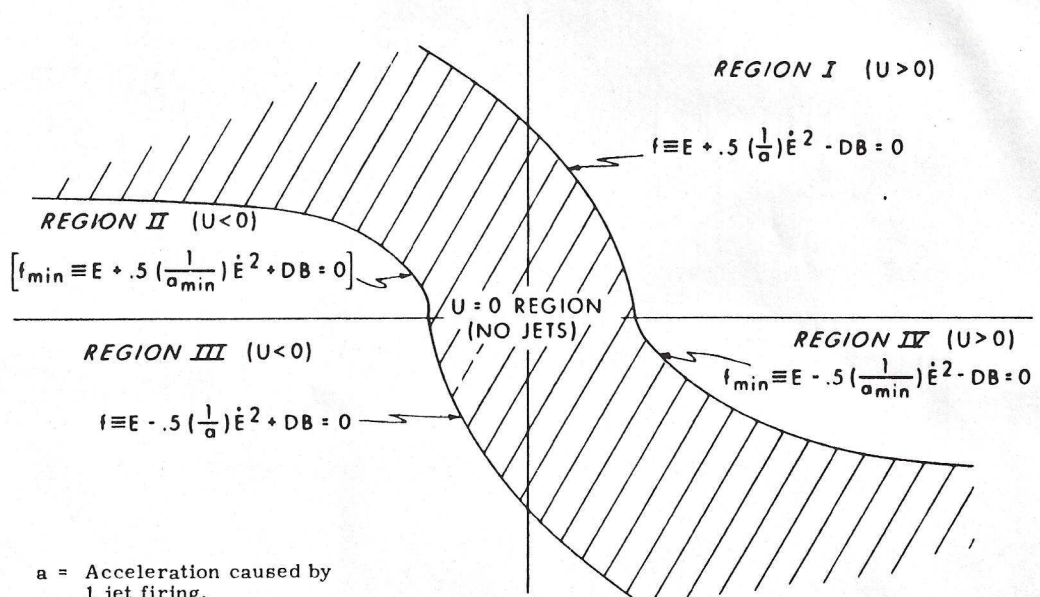
The urgency function should be a measure of the divergence of the system from a coast region as well as a measure of the penalty paid in RCS propellants if the decision to apply torque is deferred. Figure 3-8 illustrates the urgency regions for descent and drifting flight control. In region I the urgency function is

$$U = (f + \dot{E})/a$$

as shown in Fig. 3-9. Note that f is the horizontal distance from the boundary of the coast region to the phase point. \dot{E} is the rate at which this distance is increasing. Thus $f + \dot{E}$ is the number of units of attitude error which will exist in one unit of time. This distance is then normalized by a control acceleration to yield the urgency function. Another viewpoint for gaining insight into the urgency functions is to realize that they are roughly equal to the torquing time (1-jet torquing time) to reach the boundary of the coast region. The approximation to torquing time is made in order to avoid taking a square root during the urgency function calculation, as shown in Fig. 3-9. Figure 3-10 is the urgency function calculation.

Figure 3-11 illustrates the axes about which torque can be applied. The arrows depict the thrust applied by the i^{th} jet. The U and V axes are rotated 45° from the y - z axes (i. e., from the Q-R axes).

The urgency plane for picking the desired axis of rotation is illustrated in Fig. 3-12. The two urgency functions, U_Q and U_R , define the position in



a = Acceleration caused by
1 jet firing.

$a_{\min} = .02$

For Regions I and III, the urgency FCT is $U = \frac{1}{a} (f + \dot{E})$

For Regions II and IV, the urgency FCT is $U = \frac{1}{a} f_{\min}$

In Regions I and IV, $U > 0$ and negative jets must be fired.

In Regions II and III, $U < 0$ and positive jets must be fired.

Fig. 3-8 Urgency Region for Descent and Drifting Flight

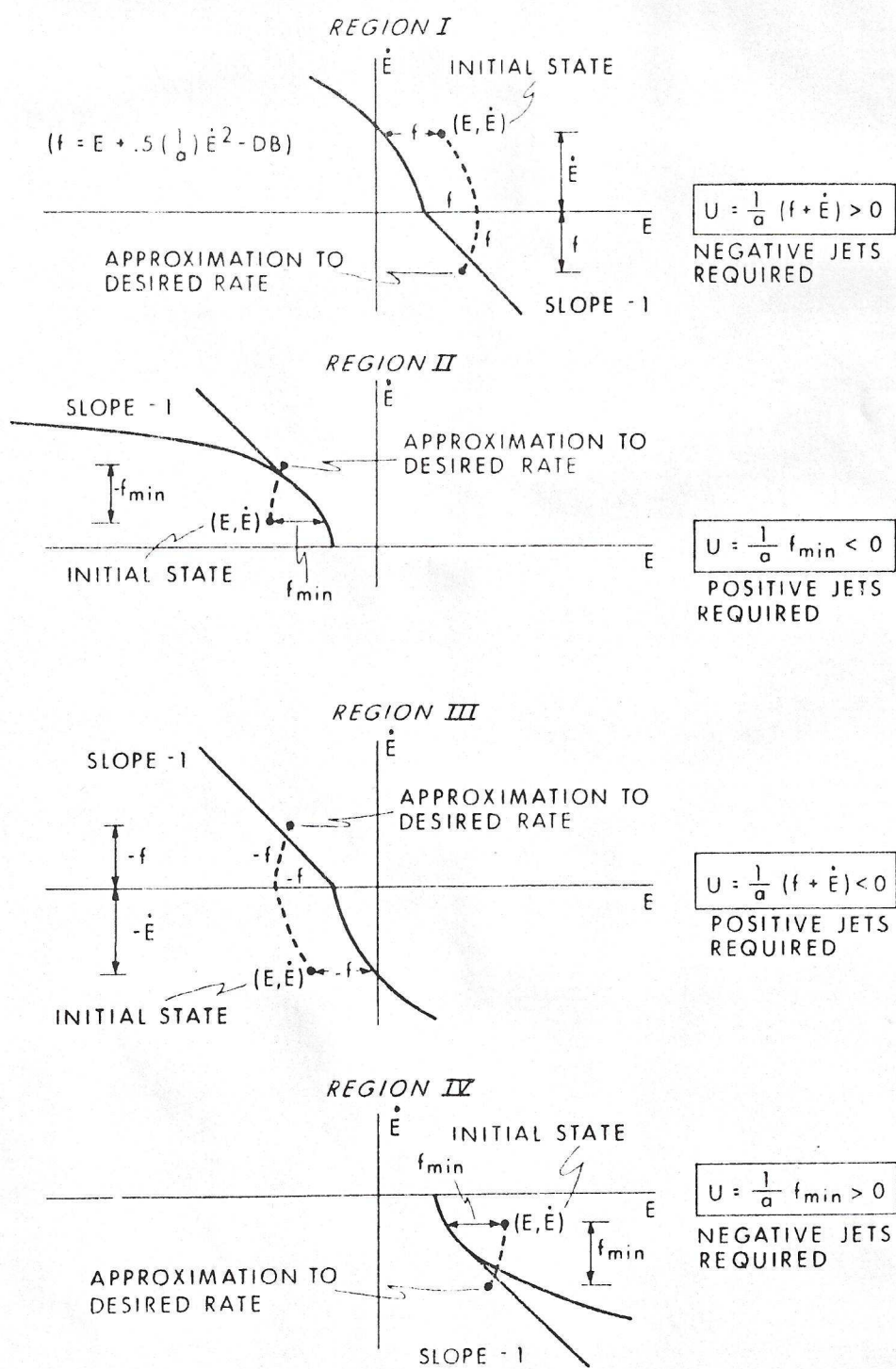


Fig. 3-9 Urgency Functions (View as Approximate T_{jet} Times)

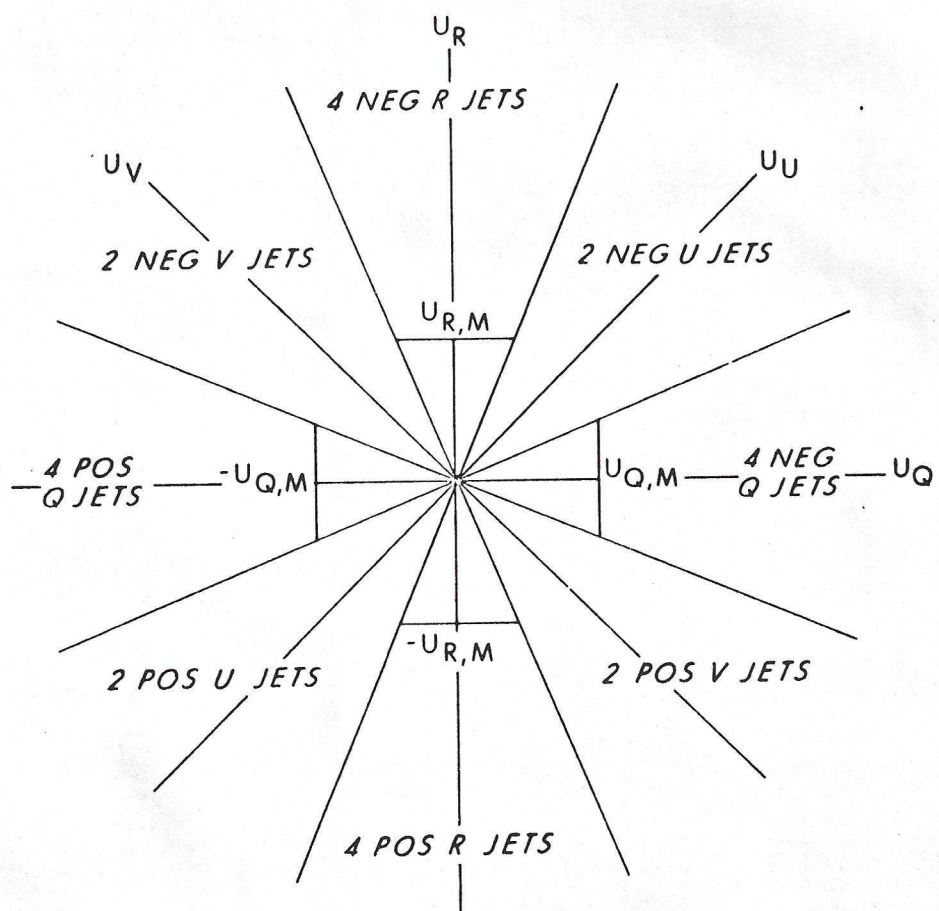


Fig. 3-12 Urgency Plane for Descent and Drifting Flight

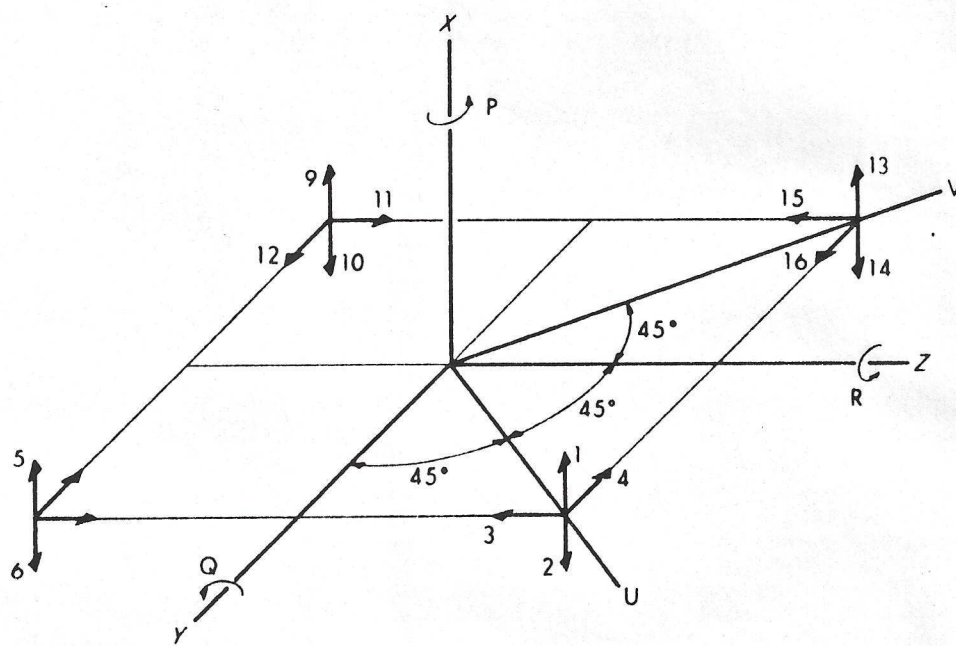


Fig. 3-11 Location of Torque Axes in LEM Showing Diagonal Axes U and V

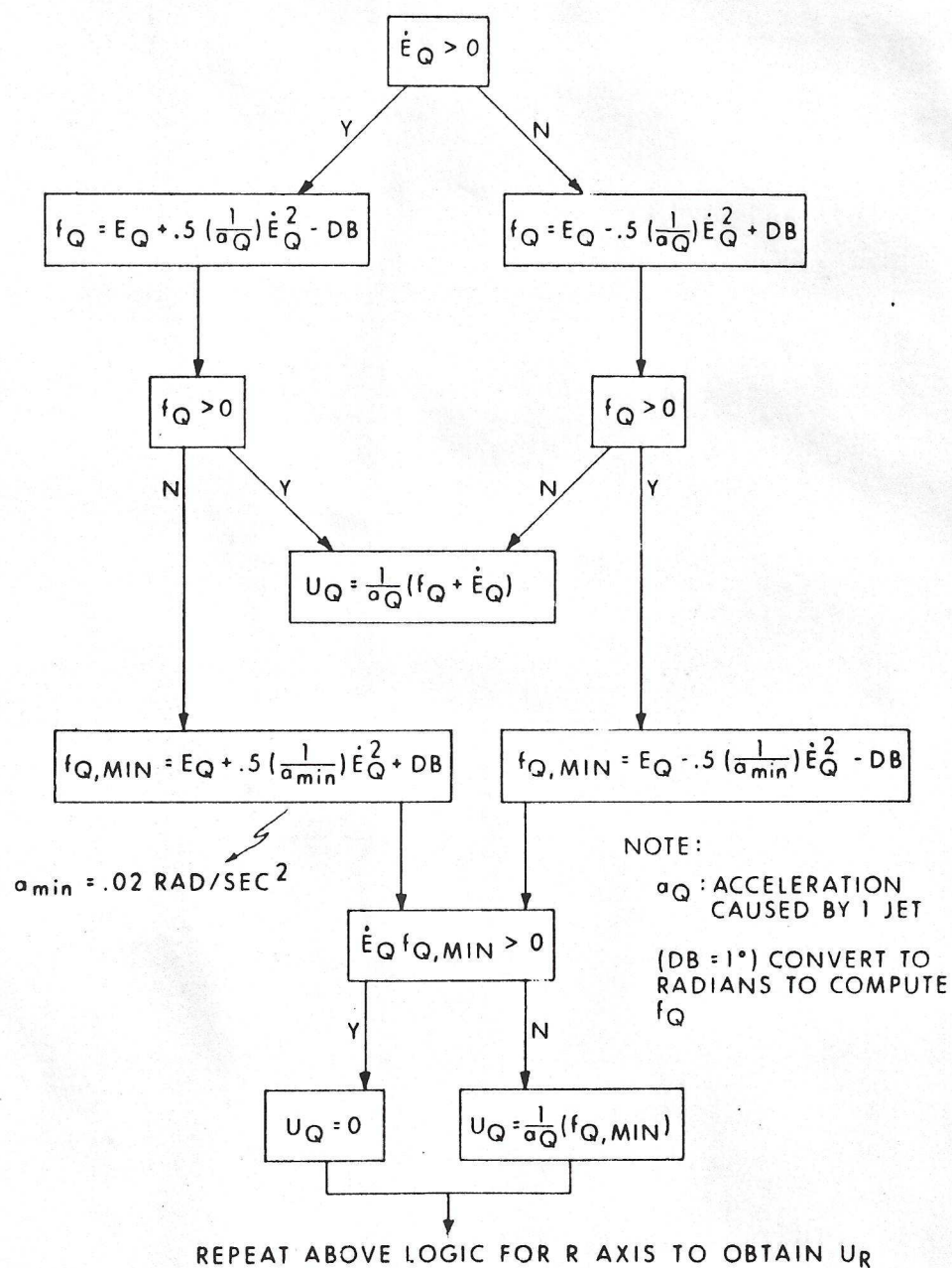


Fig. 3-10 Descent and Drifting Flight Urgency Calculation

the urgency plane and thus pick the axis and direction of rotation. Figure 3-13 is a flow graph of the logic which chooses the axis of rotation, the direction of rotation, and the number of jets used to provide the rotation.

3.3.6 Attitude Steering Control Equations (Ascent)

During Ascent engine burning the disturbing angular acceleration due to the APS cannot be reduced. If the descent and drifting flight control law is used, a very high frequency of jet firings would result. Another difference between DPS attitude steering and APS attitude steering exists: during ascent only +X Pitch-Roll thrusters should be used (unless the disturbing angular acceleration becomes too great for two jets to control). These considerations have led to a different ascent control law.

The most efficient limit cycle for operation with a large disturbing acceleration is illustrated in Fig. 3-14. The disturbing acceleration due to the main engine offset, a_{os} , carries the phase point from A to B, just skimming the edge of the deadband; the control jet acceleration minus the disturbing acceleration is used to carry the phase point back to A. The policy of just skimming the deadband when under influence of the disturbing acceleration is somewhat hazardous from the propellant point of view. If the estimate of a_{os} is too small the path from A to B may pass beyond the deadband causing the control jets to fire in the direction of the disturbing acceleration, and thereby wasting fuel. The dotted path of return is a safer one to try to attain.

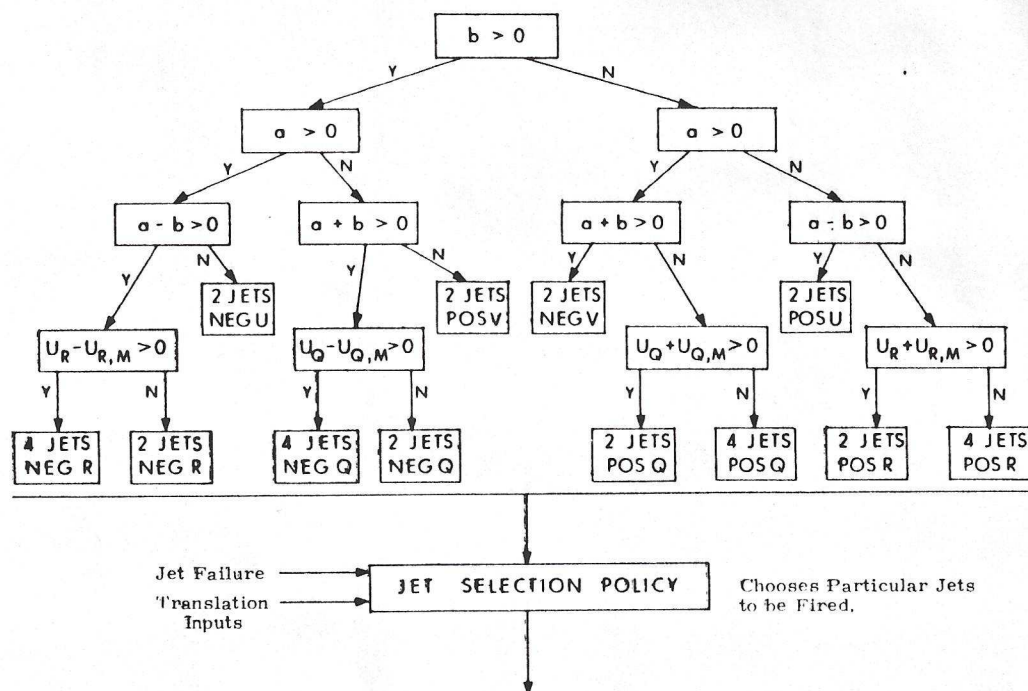
Figures 3-15 through 3-21 refer to the Pitch-Roll ascent control problem. Figure 3-15 is the phase plane representation of the T_{jet} computation. Figure 3-16 is the flow graph for the T_{jet} computation. Figures 3-17 through 3-21 refer to the urgency function calculations. These figures are largely self-explanatory.

3.3.7 Pitch-Roll Jet Select Logic

After the direction and number of jets to be fired in the Pitch-Roll section of the Digital Autopilot have been determined, it is necessary to determine which bit configurations should be written into Channels 5 and 6 to turn on appropriate (unfailed) jets. Channel 32 of the LGC is sampled every 250 ms to determine which jets have failed off and thus cannot be used in any firing policy.

Given a code to indicate the rotation, direction, and number of jets to be fired, a routine determines the best firing policy based on the detected jet failures and provides the number and direction of the Q and R axis jets actually fired to the torque vector reconstruction routine, for the rate derivation. If a failure is detected such that the best policy for a particular maneuver cannot

$$\text{COMPUTE } \begin{cases} a = U_R \cos(22.5^\circ) - U_Q \sin(22.5^\circ) \\ b = U_R \sin(22.5^\circ) + U_Q \cos(22.5^\circ) \end{cases}$$



The number of jets to be fired and the axis about which torque is applied has been determined in the above logic. The number of jets may be modified if it is desired to translate.

When the axis and number of jets has been determined, the angular acceleration about the axis is computed. This acceleration (n_{JETACC}) is used in the jet on-time calculation.

Fig. 3-13 Axis-of-Rotation Selection for Descent and Drifting Flight

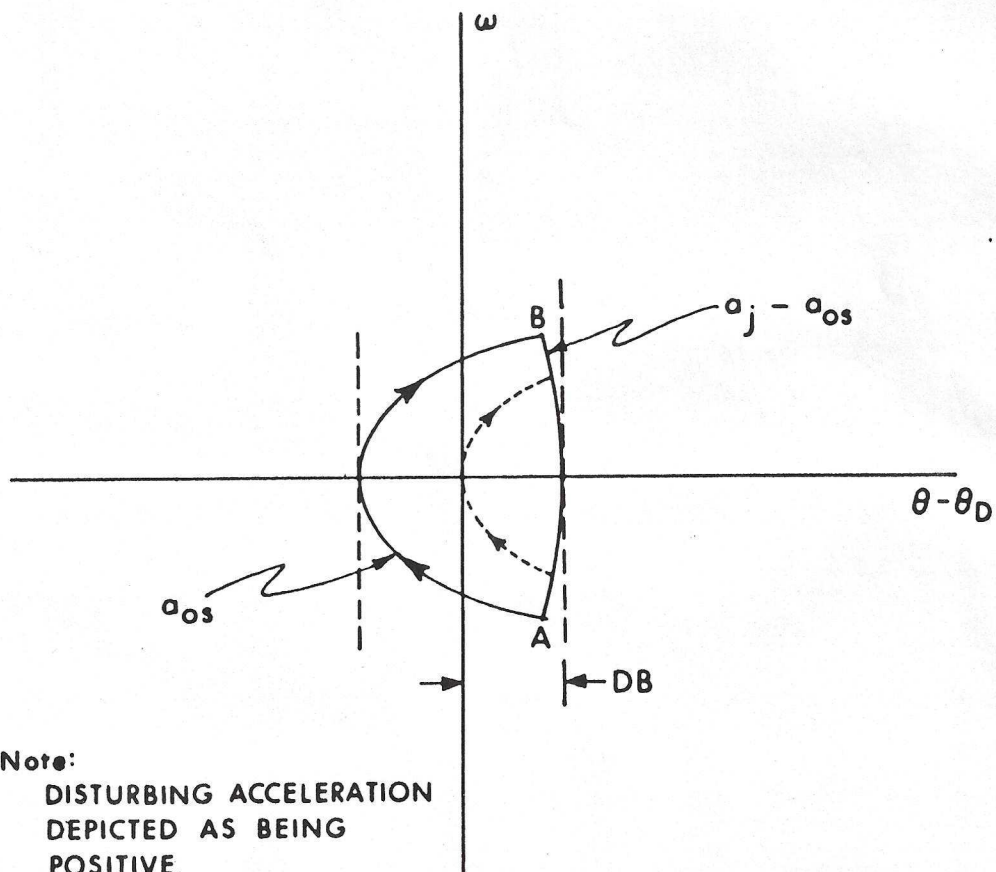
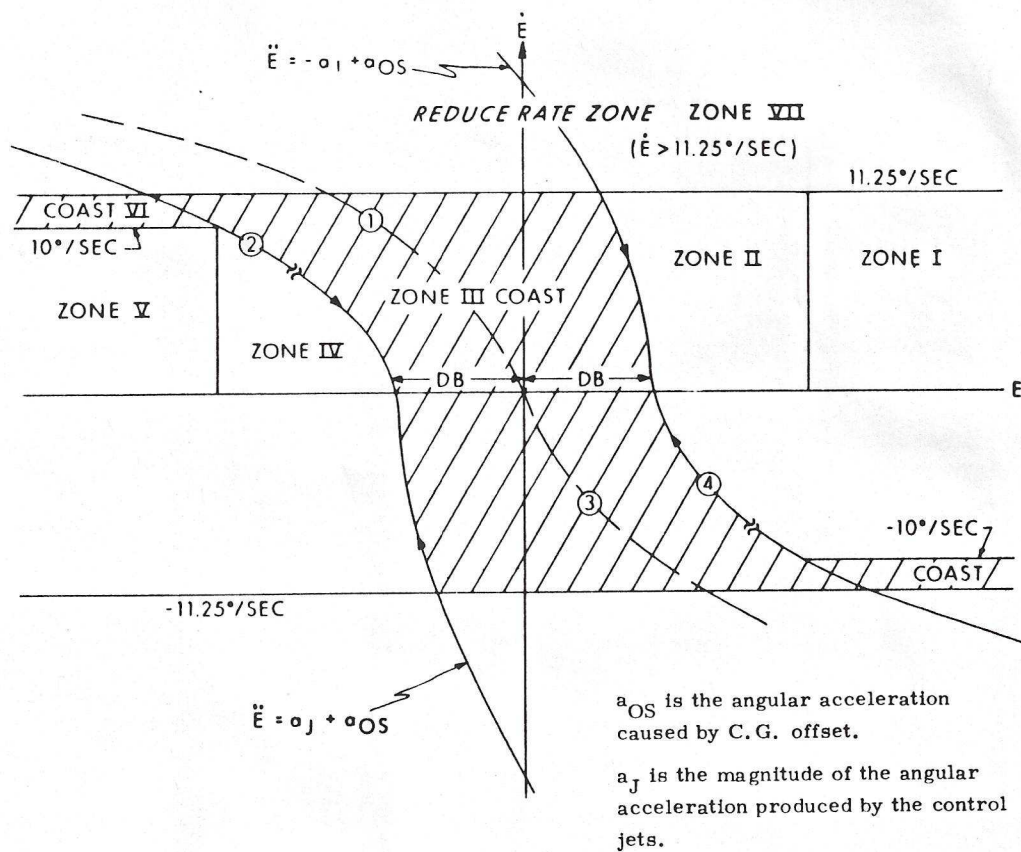


Fig. 3-14 Most Efficient Limit Cycle under a Large
Disturbing Angular Acceleration.



Curves 1 and 2 have the same acceleration.
Curves 3 and 4 have the same acceleration.

Case 1. $a_{OS} > 0$

For Curves 1 and 2, $\ddot{E} = -.02 \text{ rad/sec}^2$

For Curves 3 and 4, $\ddot{E} = \max(a_{OS}, .02)$

From Zone II, jet on-time is computed to intersect curve 3. From Zone IV, jet on-time is computed to intersect curve 2.

Case 2. $a_{OS} < 0$

For Curves 1 and 2, $\ddot{E} = -\max(-a_{OS}, .02)$

For Curves 3 and 4, $\ddot{E} = .02$

From Zone II, jet on-time is computed to intersect curve 4. From Zone IV, jet on-time is computed to intersect curve 1.

Fig. 3-15 Phase Plane for Computing T_{jet} with a Large Disturbing Acceleration.

NOTE:

In this Fig, A_j is defined as the magnitude of the angular acceleration produced by the control jets.

$nJETACC$ is the magnitude of the net acceleration (includes offset acceleration.)

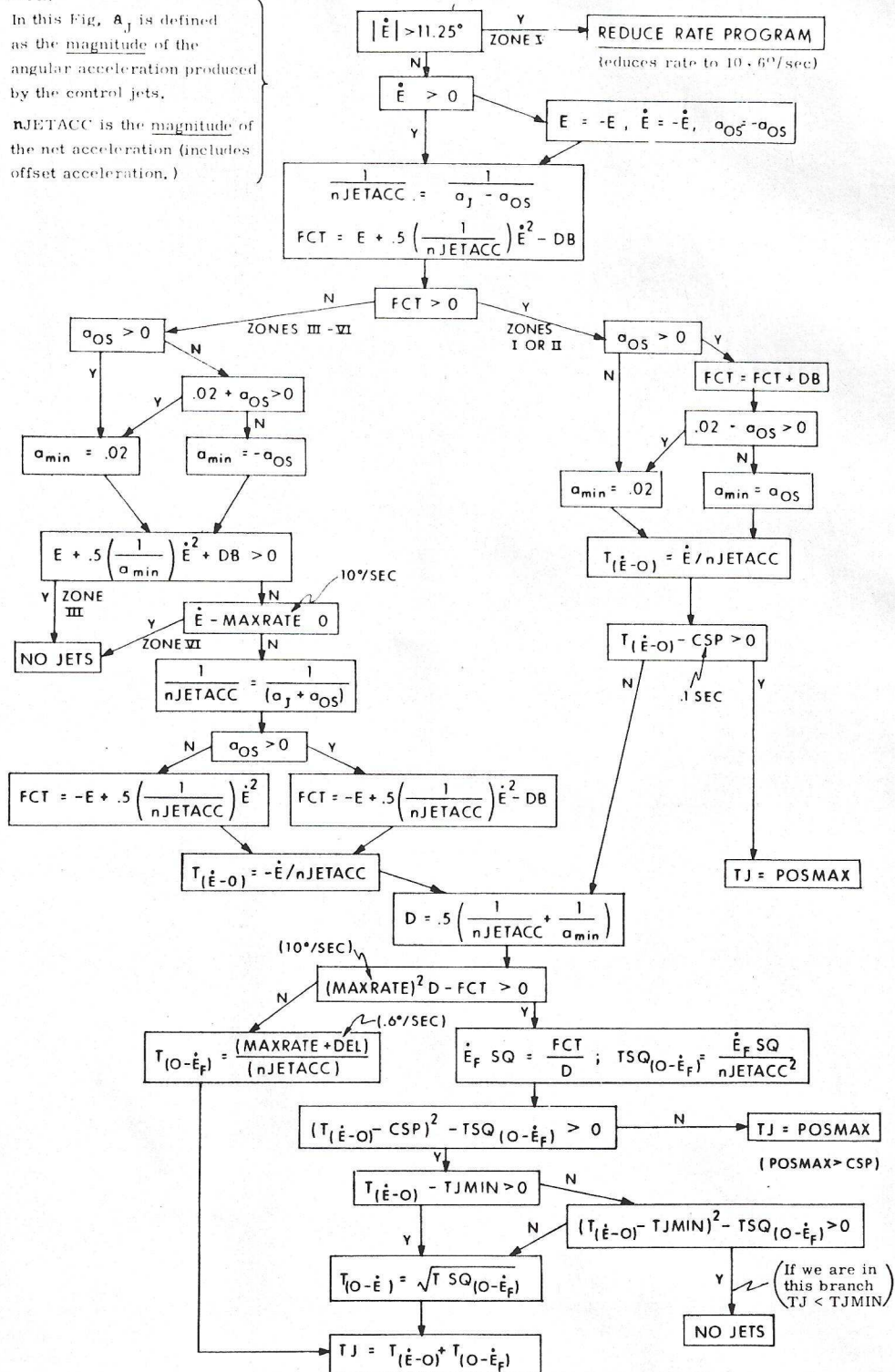
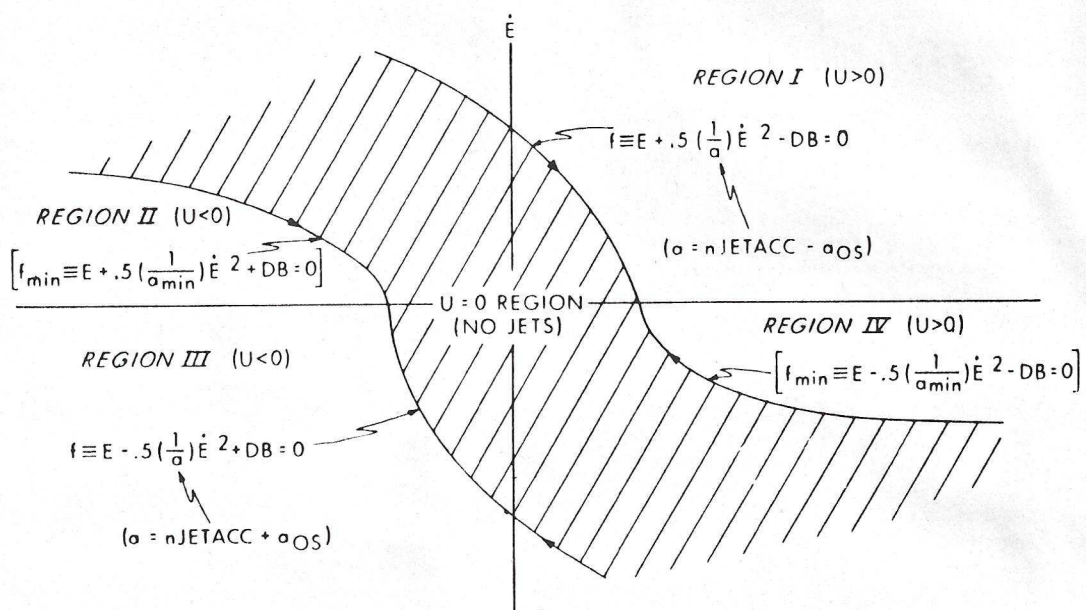


Fig. 3-16 Flow Graph for Computing T_{jet} with a Large Disturbing Acceleration.



NOTES: a_{OS} is the acceleration resulting from C.G. offset. a_{OS} may be positive or negative.

In Region II, If $a_{OS} > 0$, $a_{min} = .02 \text{ rad/sec}^2$
 If $a_{OS} < 0$, $a_{min} = \max(-a_{OS}, .02)$

In Region IV, If $a_{OS} > 0$, $a_{min} = \max(a_{OS}, .02)$
 If $a_{OS} < 0$, $a_{min} = .02 \text{ rad/sec}^2$

$nJETACC$ is the magnitude of acceleration produced by n jets, and A is the magnitude of net acceleration (includes a_{OS}) produced by n jets. $n = 2$ if it yields a value of $a > .02 \text{ rad/sec}^2$. If $n = 2$ yields a value of $a < .02 \text{ rad/sec}^2$, then n is set equal to 4.

For Regions I and III, the urgency function is: $U = \frac{1}{a} (f + \dot{E})$

For Regions II and IV, the urgency function is: $U = \frac{1}{a} f_{min}$

In Regions I and IV, $U > 0$ and negative jets must be fired.

In Regions II and III, $U < 0$ and positive jets must be fired.

Fig. 3-17 Urgency Regions for Axis Selection with a Large Disturbing Acceleration.

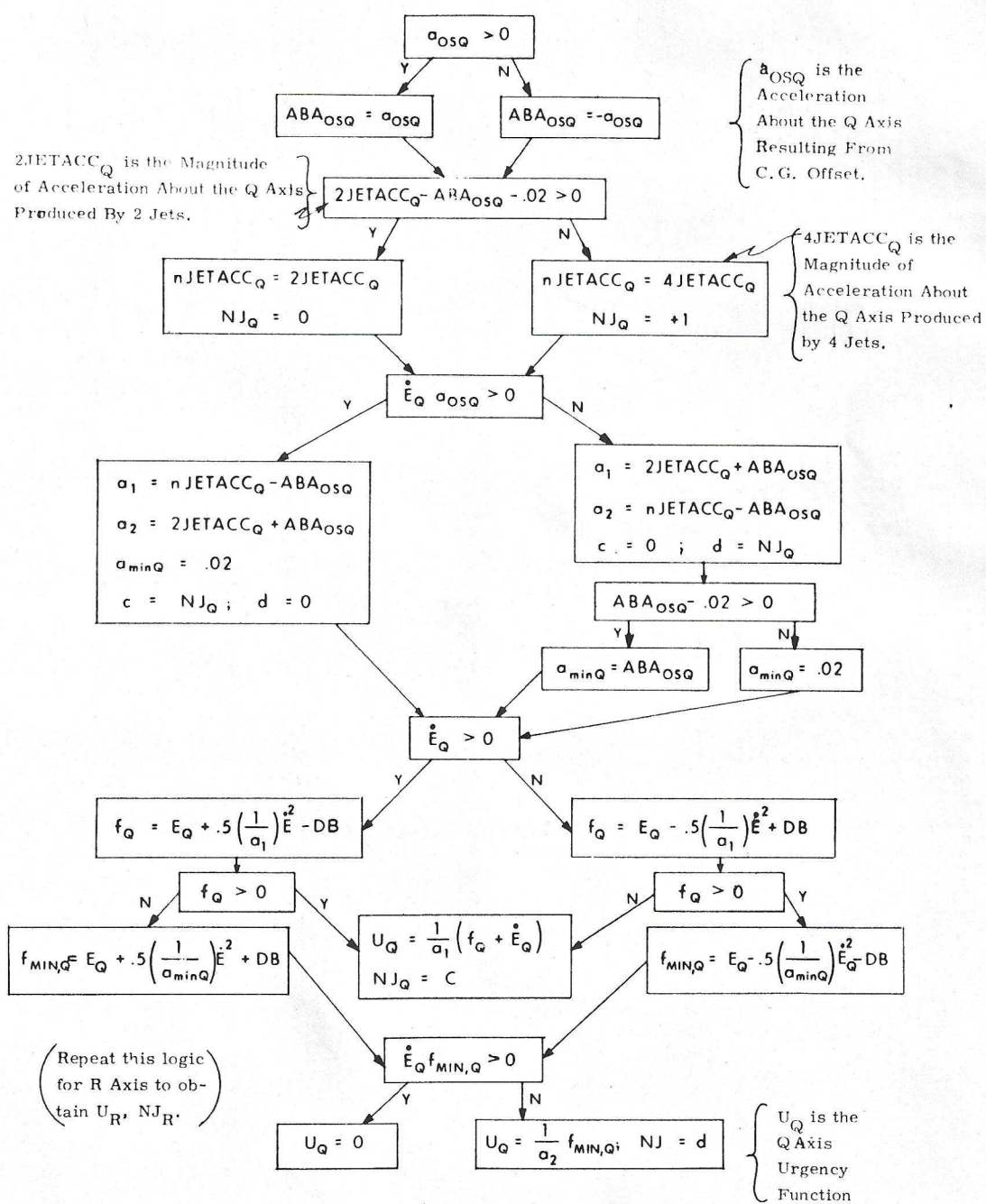
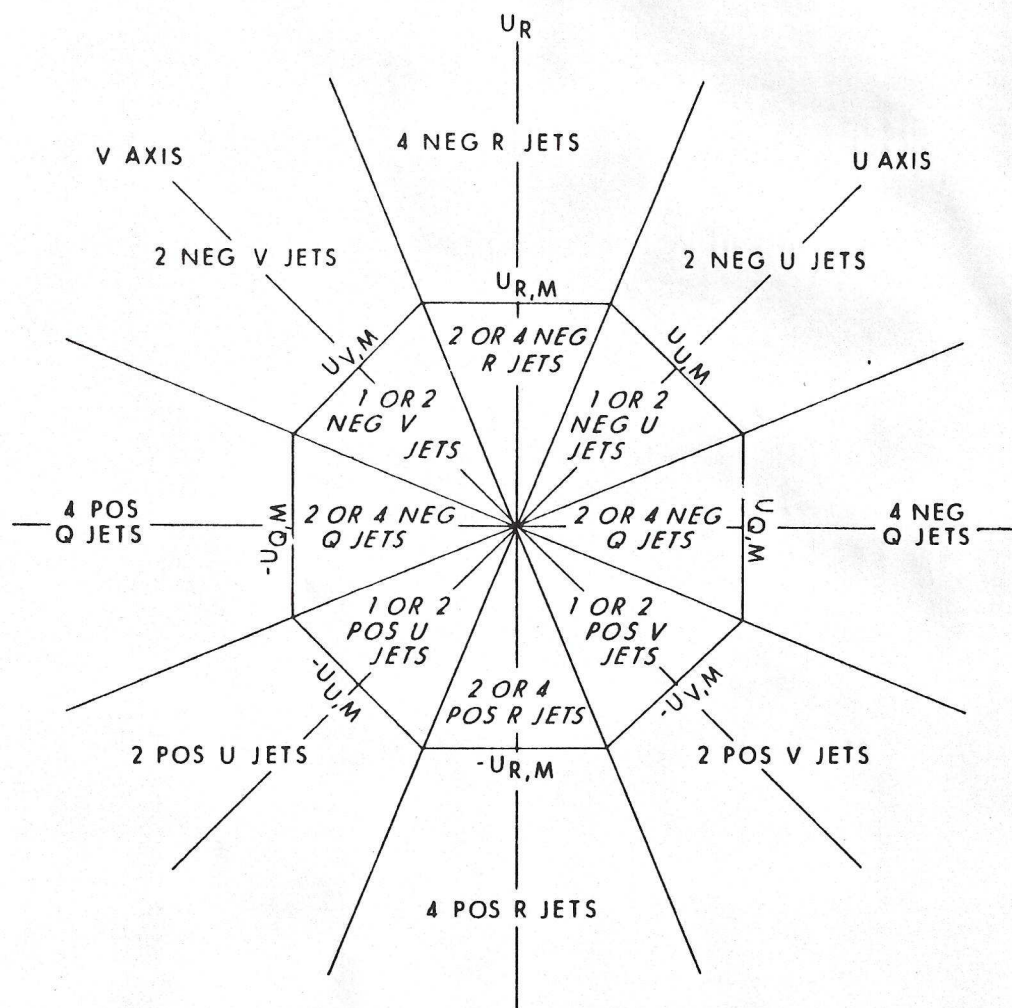


Fig. 3-18 Urgency Logic for Q-R Axes with a Large Disturbing Acceleration.



NOTE: In the regions where a choice is given between 2 or 4 jets (or 1 or 2 jets), the larger number of jets is used only if the net acceleration caused by the smaller number of jets is less than $.02 \text{ rad/sec}^2$. Net acceleration includes a_{OS} (C.G. offset acceleration).

Fig. 3-19 Q-R Urgency Plane for a Large Disturbing Acceleration

$$\text{COMPUTE } \begin{cases} a = U_R \cos(22.5^\circ) - U_Q \sin(22.5^\circ) \\ b = U_R \sin(22.5^\circ) + U_Q \cos(22.5^\circ) \end{cases}$$

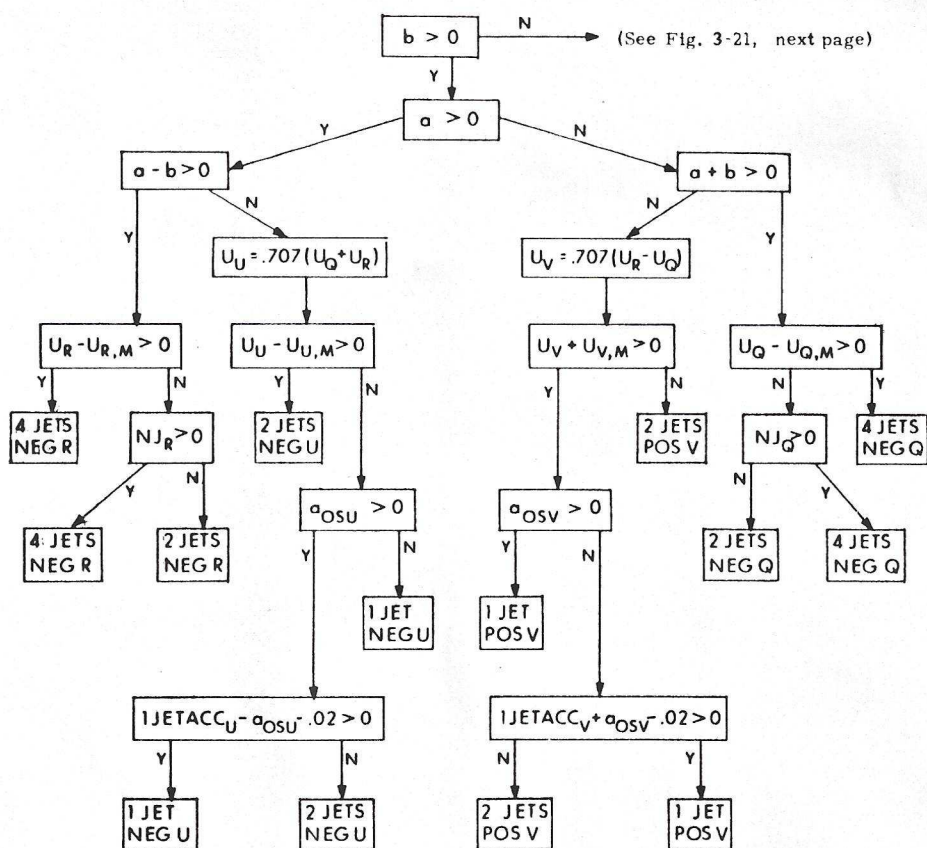
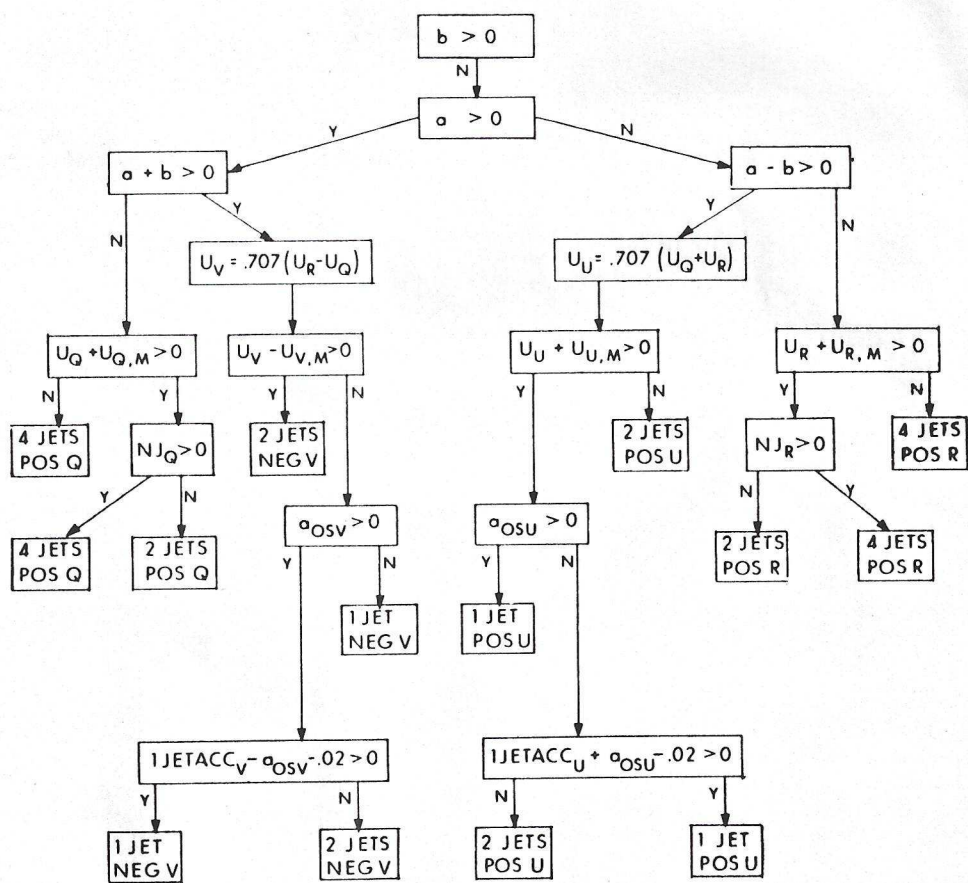


Fig. 3-20 Axis Selection Logic Using Urgency Functions
Computed from Fig. 3-18 ($b > 0$)



The number of jets to be fired and the axis about which torque is applied has been determined in the above logic.

The angular acceleration about the axis which has been chosen must be computed. This acceleration (a_j) is used in the jet on-time calculation.

Fig. 3-21 Axis Selection Logic Using Urgency Functions
Computer from Fig. 3-18 ($b < 0$)

be requested a policy of either equal or partially degraded performance is tested for jet failure. If the jet failures occur to such an extent that of n possible combinations of jets for the maneuver the first $n-1$ are found to be impossible then the last (n^{th}) policy is selected.

All this is done with a minimum of calculation since the entire routine is table-driven as shown in Fig. 22.

3.3.8 Rate Derivation

This section describes how the vehicle's rate is calculated during the jet activity periods of the digital autopilot. Because the actual RCS jet torque may not be equal to the nominal torque (in fact, a jet failure may have occurred and not been detected), heavy filtering of the vehicle's derived rate is not effective during the jet activity periods. (We cannot accurately extrapolate the old rate to the current time with a poor model of the jet torque). Nevertheless, some filtering is clearly desirable. The rate filter is a simple feedback system which predicts what vehicle rotation should be measured and subtracts this prediction from the vehicle's measured rotation. A fraction of the discrepancy between the measured rotation and the predicted rotation is attributed to error in the rate signal, which is appropriately adjusted.

There are two ways to derive the equations used to mechanize the filter. The first way is purely intuitive.

The differential equation for the vehicle's rate is

$$\underline{\dot{M}} = \underline{J} \underline{\dot{\omega}} + \underline{\omega} * \underline{J} \underline{\omega} \quad (3-1)$$

The small angular rate approximation allows us to neglect the second term and rewrite Eq. 3-1 as the following linear differential equation

$$\underline{\dot{\omega}} = \underline{F} \underline{M} \quad (3-2)$$

where

$$\underline{F} = \underline{J}^{-1} \quad (3-3)$$

From Eq. 3-2 we can develop the following state transition equations for the spacecraft's angular rate vector and small rotation vector

$$\underline{\Delta}_n = \underline{\omega}_{n-1} (t_n - t_{n-1}) + \int_{t_{n-1}}^{t_n} (t_n - t) \underline{F} \underline{M}(t) dt \quad (3-4)$$

$$\underline{\omega}_n = \underline{\omega}_{n-1} + \int_{t_{n-1}}^{t_n} \underline{F} \underline{M}(t) dt \quad (3-5)$$

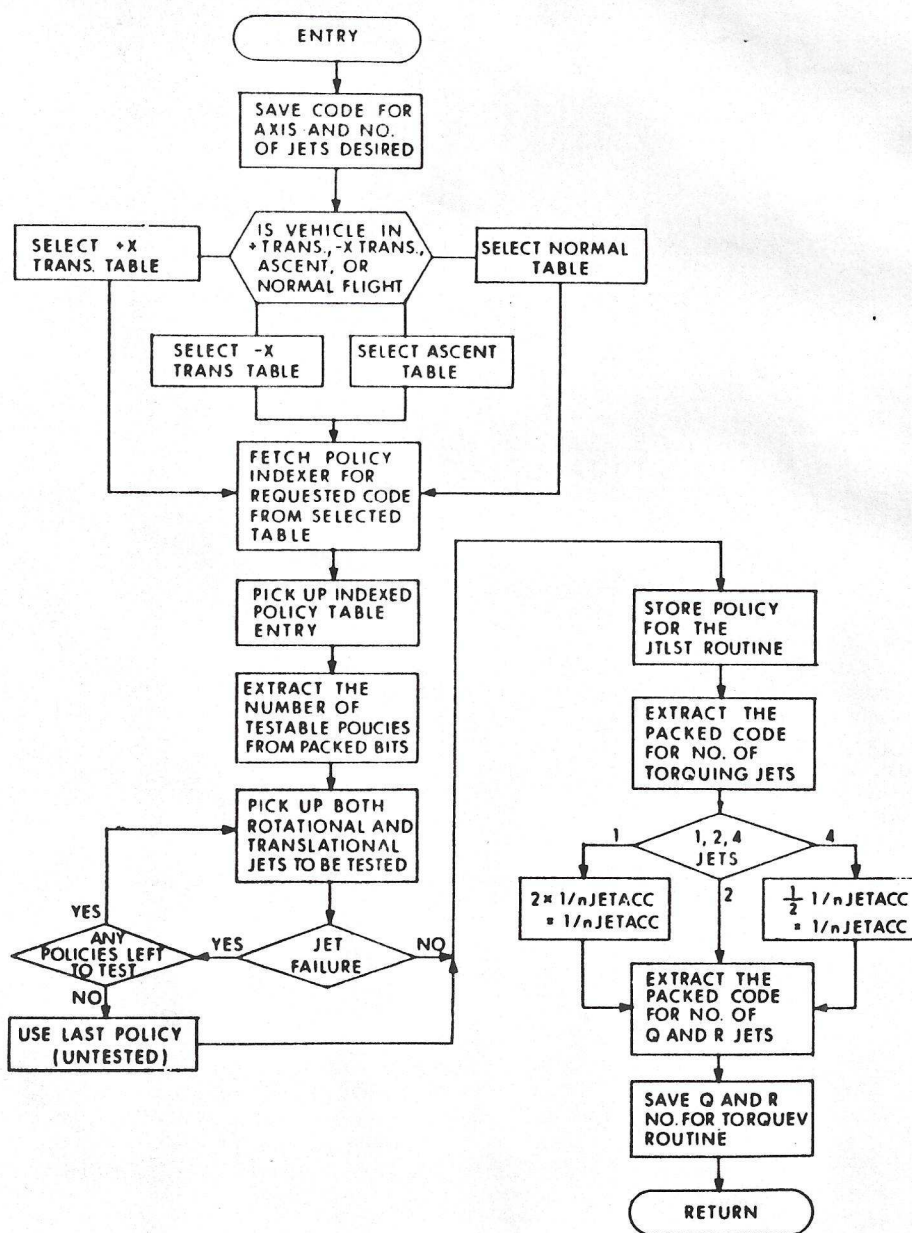


Fig. 3-22 Q-R-Axes Jet-Policy Selection Logic

By solving Eq. 3-4 for $\underline{\omega}_{n-1}$ and substituting the results into Eq. 3-5 we can arrive at the following expression for $\underline{\omega}_n$.

$$\underline{\omega}_n = \underline{\Delta}_n / (t_n - t_{n-1}) - \left[\int_{t_{n-1}}^{t_n} (t_n - t) F^* \underline{M}(t) dt \right] / (t_n - t_{n-1}) + \int_{t_{n-1}}^{t_n} F^* \underline{M}(t) dt \quad (3-6)$$

Equation 3-6 represents a derivation of rate that incorporates no smoothing at all. On the other hand, Eq. 3-5 represents a derivation of rate that incorporates infinite smoothing, i.e., zero use of the measured rotation, $\underline{\Delta}_n$. By weighting and combining Eq. 3-5 and Eq. 3-6 we can adjust the degree of smoothing between zero smoothing, Eq. 3-6 and infinite smoothing, Eq. 3-5. Multiplying Eq. 3-6 by K and Eq. 3-5 by (1 - K) and finally adding the two results yields

$$\underline{\omega}_n = (1 - K) \left[\underline{\omega}_{n-1} + \int_{t_{n-1}}^{t_n} F^* \underline{M}(t) dt \right] + K \left[\underline{\Delta}_n / (t_n - t_{n-1}) - \int_{t_{n-1}}^{t_n} (t_n - t) F^* \underline{M}(t) dt / (t_n - t_{n-1}) + \int_{t_{n-1}}^{t_n} F^* \underline{M}(t) dt \right] \quad (3-7)$$

where

K = 0: infinite smoothing

K = 1: no smoothing

In Eq. 3-7 $\underline{\Delta}_n$ represents the measured rotation between t_{n-1} and t_n , $\underline{\omega}_{n-1}$ represents the estimate of rate at t_{n-1} , and $\underline{M}(t)$ represents the torque commanded between t_{n-1} and t_n .

The second way to derive Eq. 3-7 is by examining the Kalman linear recursive filter equation. (For a discussion of the notation and ideas involved here, see R-499.) The Kalman linear recursive form is

$$\hat{\underline{\omega}}_n = \hat{\underline{\omega}}_{n-1} + w (\tilde{\underline{\Delta}}_n - \underline{\Delta}_{n-1}) \quad (3-8)$$

Substituting Eqs. 3-4 , 3-5 into Eq. 3-8 yields

$$\begin{aligned} \hat{\omega}_n = \hat{\omega}_{n-1} + \int_{t_{n-1}}^{t_n} \dot{F} \underline{M}(t) dt \\ + w \left\{ \tilde{\Delta}_n - \omega_{n-1} (t_n - t_{n-1}) - \int_{t_{n-1}}^{t_n} (t_n - t) \dot{F} \underline{M}(t) dt \right\} \end{aligned} \quad (3-9)$$

If

$$w = K/(t_n - t_{n-1}) \quad (3-10)$$

is substituted into Eq. 3-9 , Eq. 3-9 becomes identical to Eq. 3-7 .

3.3.9 The Trim Gimbal Servo

For some time it has been known that attitude hold could be performed by the DPS trim gimbal. Thus, the trim gimbal can cause the LEM to limit cycle inside the RCS jet dead band. (See Fig. 3-23). The gimbaled DPS engine can actually impress very large torques on the LEM, on the order of 10 times the torque due to the firing of a single RCS jet. (See Fig. 3-24). The advantage of the RCS jets for the control function is that they generate their torques very quickly upon receiving a command. When a quiescent jet is commanded to thrust, the delay before full thrust and torque is achieved is only a matter of milliseconds. On the other hand, if the thrust vector of the DPS engine passes through the c.g., approximately 30 seconds are required before the maximum lever arm of the moment can be achieved by gimbaling the DPS engine! (The gimbal angle changes at the rate of $0.2^\circ/\text{sec.}$) Another 30 seconds are required to return the gimbal to the zero moment arm position.

The slowness of the trim gimbal quite evidently makes it unsuitable for the control function when the steering commands are changing rapidly. Thus, during phase 2 (the visibility phase) when the radar data is being assimilated in the navigation and guidance system (causing the steering errors to fluctuate a great deal) and the astronaut is causing site redesignations, a trim gimbal law which attempts to steer the spacecraft is of marginal or even negligible utility.

But during the major portion of the first phase of the landing trajectory, when the steering commands change in a smooth and gradual manner, the trim gimbal should be fast enough to steer the LEM without the assistance of RCS jet firings.

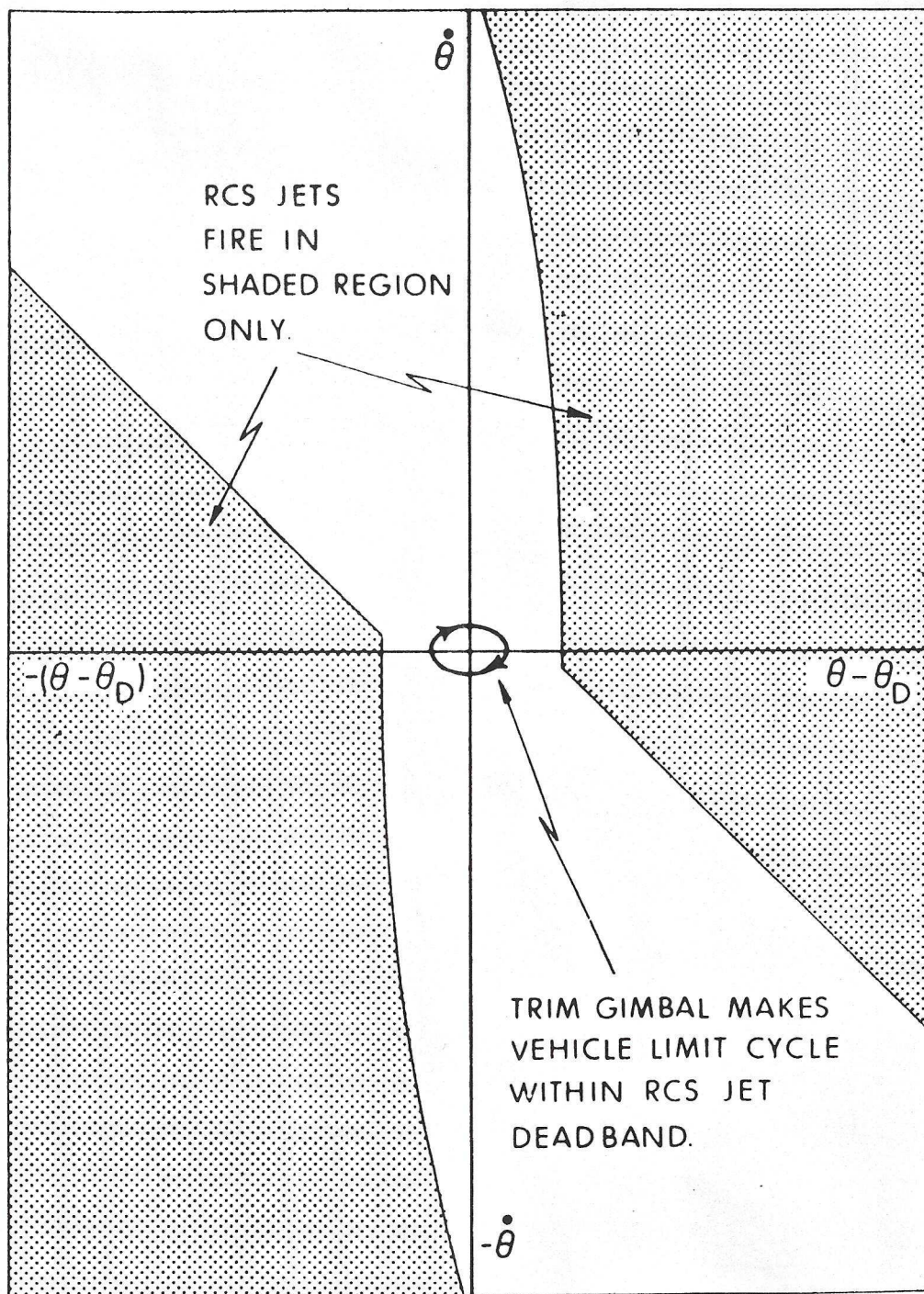
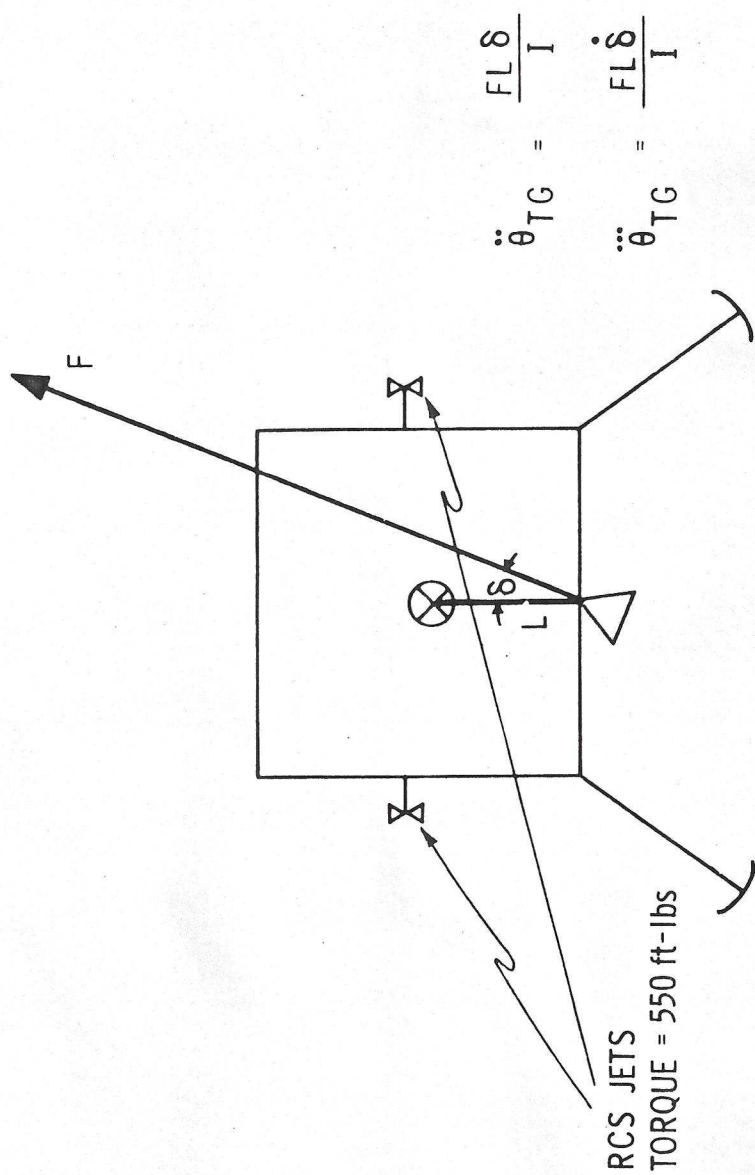


Fig. 3-23 Controlling the LEM Attitude and Attitude Rate with the Trim Gimbal



MAX. TORQUE FROM DPS \approx 5000 ft-lbs (for $\delta = 6^\circ$)

$\dot{\delta} = \pm 0.2^\circ/\text{sec}$ MAXIMUM $\delta \approx 6^\circ$

Fig. 3-24 LEM Control Torque Agents

Because the trim gimbal is so slow, a control law which does not add to the slowness in reacting to attitude errors is required if the RCS jets are not going to have to fire. The faster the trim gimbal control law the better. A time-optimal system of control is the most desirable kind of control here. There is no penalty connected with running the trim gimbal drive. Therefore, a time-optimal control is the correct pay-off function.

The following modified time-optimal control law is being used.

$$K = 0.3 \text{ FLR/I}$$

$$\Delta = - \text{sgn} (K \dot{\theta} + \ddot{\theta} / \ddot{\theta} / 2)$$

$$U = - \text{sgn} \left[K^2 (\theta - \theta_D) + \ddot{\theta}^3 / 3 - \Delta K \dot{\theta} \ddot{\theta} - \Delta (-\Delta K \dot{\theta} + \ddot{\theta}^2 / 2)^{3/2} \right]$$

where θ is the measured angle around a controlled axis and θ_D is the desired orientation around that axis. The quantities $\dot{\theta}$ and $\ddot{\theta}$ are simply the rate and acceleration around the axis. The control law drives $\theta - \theta_D$, $\dot{\theta}$, and $\ddot{\theta}$ to zero. The quantity K is computed every second (in the guidance equations) because it changes very slowly.

The variable U is the switch command. If $U = +1$ the gimballed engine is rotated in a positive sense; if $U = -1$, the gimballed engine is rotated in a negative sense.

The time-optimal control law requires knowledge of the system state, θ , $\dot{\theta}$, and $\ddot{\theta}$. A Kalman filter is used to estimate gimbal angles, gimbal angle rate, and gimbal angle acceleration. The Kalman filter is programmed in gimbal angle coordinates because the CDU measurements and the estimation procedure are performed four times for each calculation of the control law. The matrix multiplication required to resolve from gimbal angle coordinates to body coordinates is performed only when the control law is computed. The Kalman filter is described in R-499. The Kalman filter weights are stored as a table of 90 data words in fixed storage.

The Kalman filter computation is performed 20 times a second and takes 5 milliseconds a pass.

The control law computation (both axes) takes about 9 milliseconds. Thus, without violating the 14-millisecond maximum interrupt time, the control law can be performed with a filter calculation. If the control law is calculated 5 times per second, every fourth filter execution, the following computer load results.

P axis	5 × 6 msec	=	30 msec
Filter	20 × 5 msec	=	100 msec
Control Law	5 × 9 msec	=	45 msec
Matrix Updates	2 × 3 msec	=	6 msec
			<hr/> 181 msec

Thus, about 18% of the computer time is used by the DAP during the time the trim gimbal is used to steer the vehicle.

During each pass through the control law the angular error is checked. If the error exceeds a given bound (about 1 to 2 degrees) the jets are used for control until the vehicle's state is brought closer to the origin. Before exiting from the trim gimbal law to the RCS jet control law, the trim gimbal is set to drive $\ddot{\theta}$ to zero and a waitlist call to turn off the trim gimbal in

$$T = -\ddot{\theta} / \ddot{\ddot{\theta}}$$

seconds is requested. When the jets have returned the spacecraft to the vicinity of the origin of the $\theta - \theta_D, \dot{\theta}$ phase angle, control is returned to the trim gimbal control law. The Kalman filter weights are re-initiated upon this return.

Figure 3-25 is a block diagram of the trim gimbal control law.

3.3.10 The DAPIDLER Program

A program is required to idle when the DAP is not running. DAPIDLER initiates the DAP when DAP startup is required. The DAPIDLER Program is started during a Fresh Start as shown in Fig. 3-26. The DAPIDLER program can also be started by the DAP when the DAP recognizes that DAP action is either not required or not possible.

DAPIDLER scans all the bits which indicate whether or not the DAP is needed and whether or not the IMU is ready for DAP use. The DAPIDLER program is done periodically (every 100 milliseconds) as a self-perpetuating task on T5RUPT until it is time to start the DAP. Figure 3-27 is a flow diagram of DAPIDLER. When the DAPIDLER Program detects that it is necessary and permissible to start the DAP, certain erasable registers are initialized for the DAP and the P Axis is executed in 100 milliseconds. Among other initializations, the CDU desired registers are set equal to the CDU registers; thus, initially, there is no attitude error. The guidance equations communicate with the DAP (once per second) by writing new numbers into the CDU desired registers; consequently, as soon as the guidance equations begin operating the correct numbers will be placed in the CDU desired registers and the DAP should begin torquing the vehicle to the correct orientation.

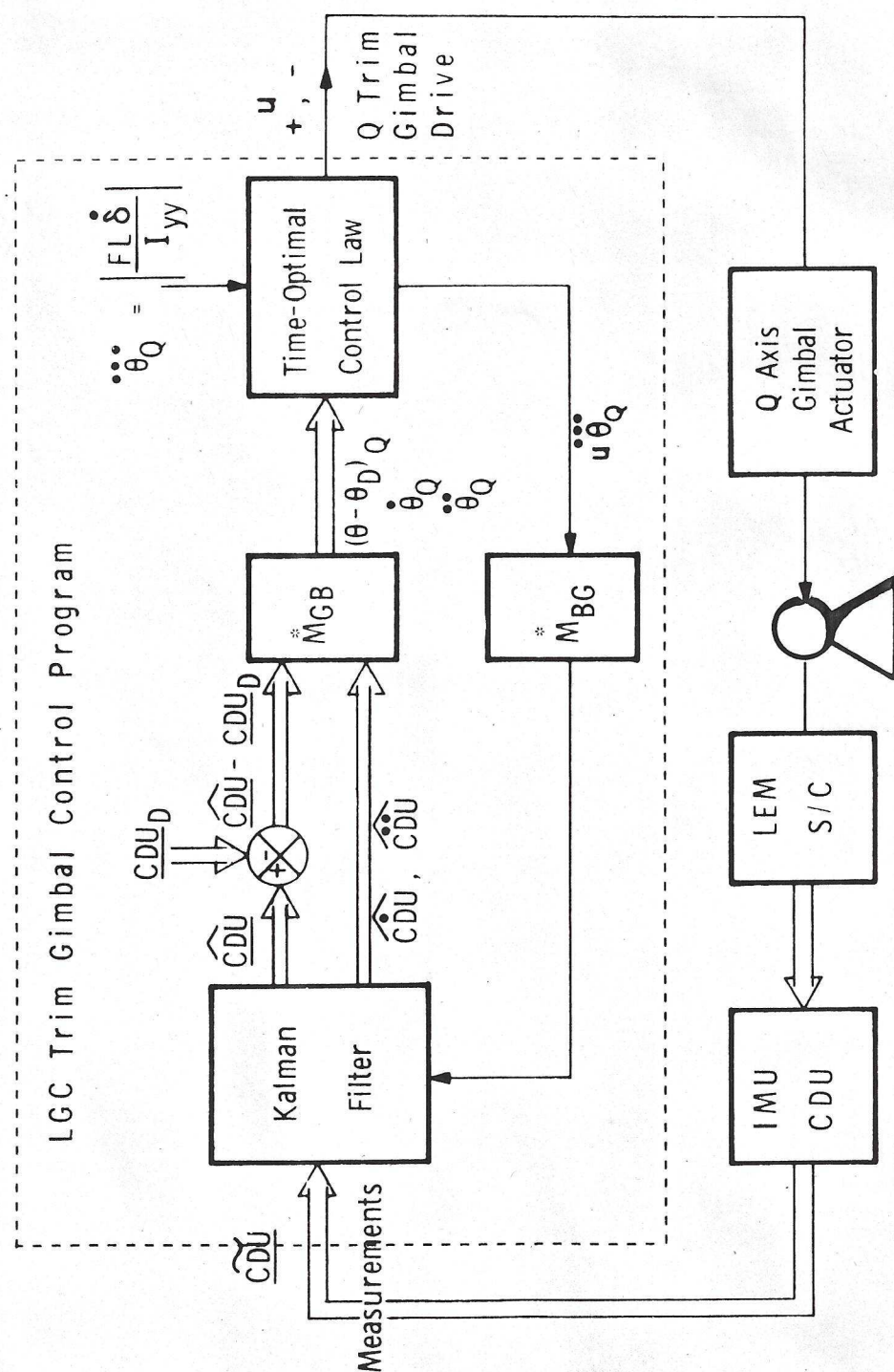


Fig. 3-25 Trim Gimbal Control System for Q Axis

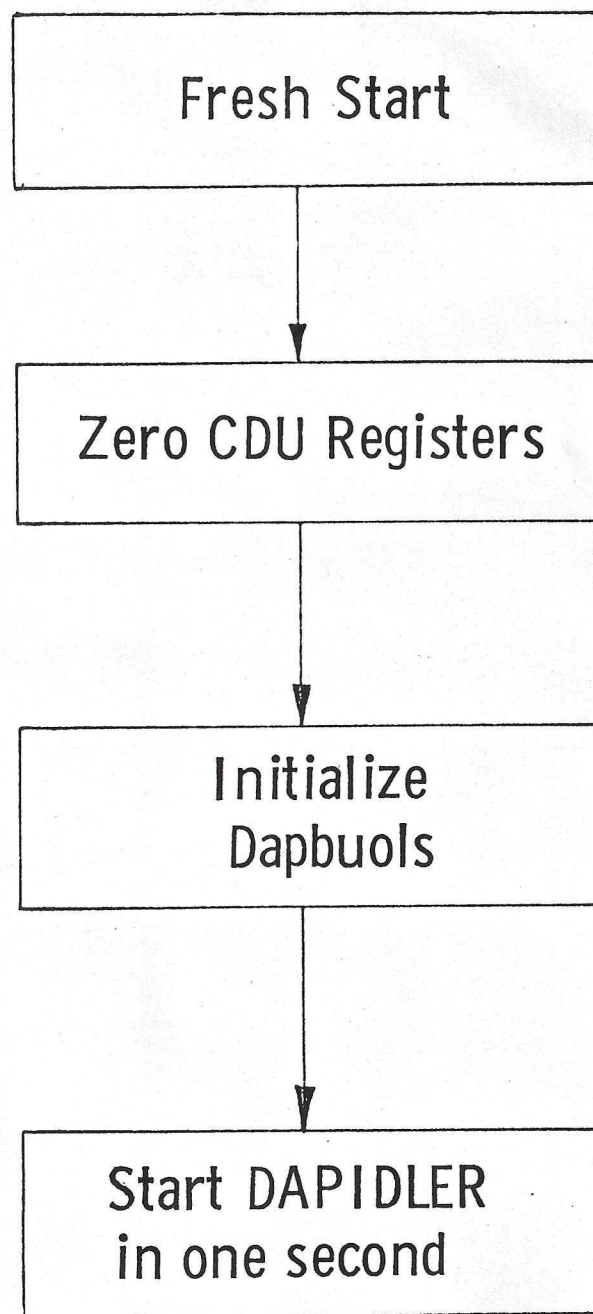


Fig. 3-26 Initiation of DAPIDLER during Fresh Start

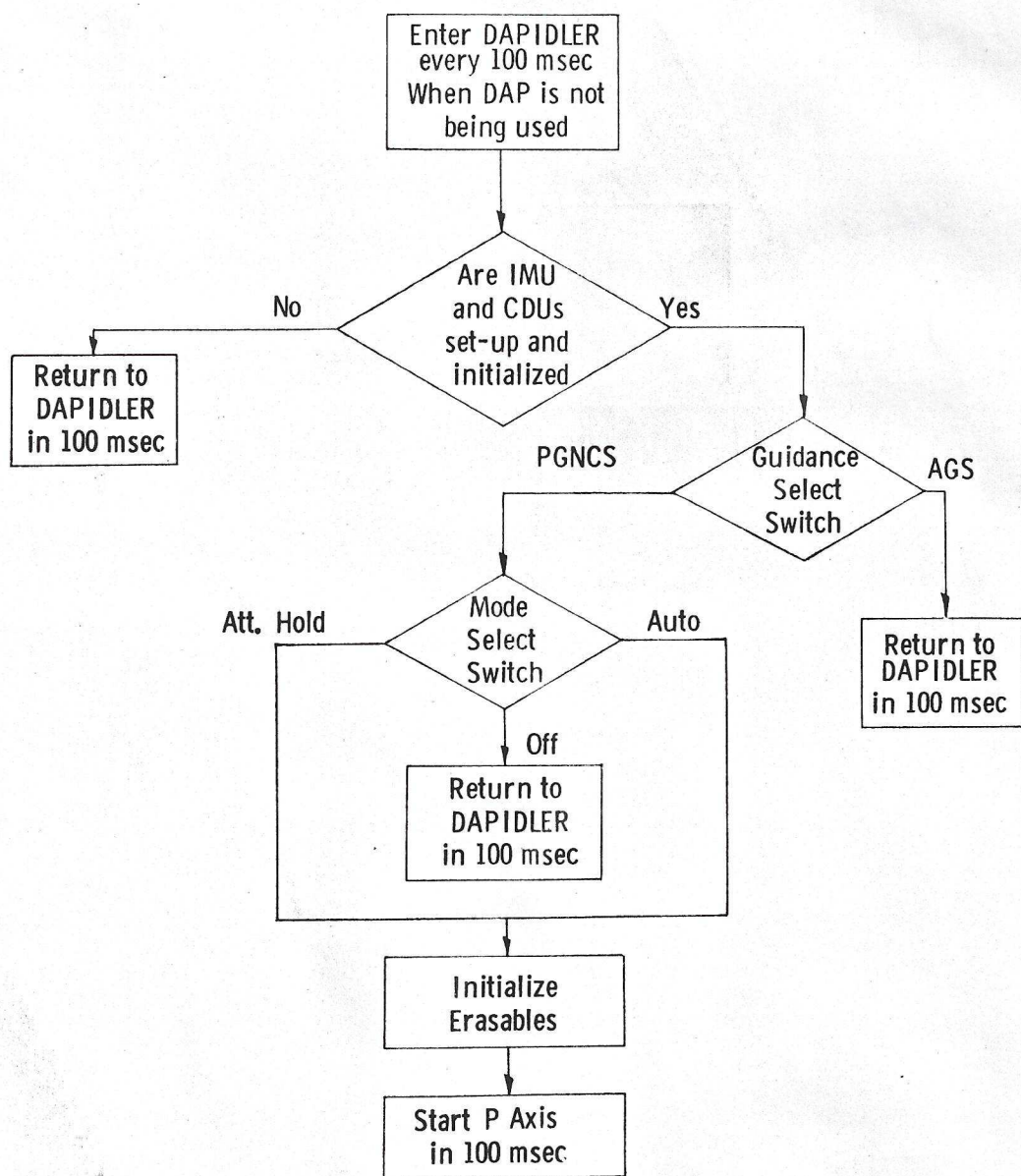


Fig. 3-27 The DAPIDLER Program

3.3.11 SPS Backup Autopilot

The LEM DAP, described in the previous pages, was designed and programmed for the LEM only, Ascent or Descent. The CSM-docked LEM DAP required modifications to existing LEM DAP programs and additional supplementary programs because of the large inertia of the CSM/LEM docked configuration and the bending and sloshing effects associated with this configuration. The precise detailed nature of the modifications to existing programs and the additional supporting programs will not be known until the official bending mode data is received. However, a design has been laid out. This design has parameters which can be varied to change the rigid body gain and rate damping and hence affect the bending body and sloshing plant stability. When the official bending mode data is available these parameters will be varied to assure stability and adequate rigid body response.

The trim gimbal control, which is very slow, is an excellent candidate for controlling the CSM-docked LEM configuration. The scaling has been adjusted so that the trim gimbal control law can work for LEM only or CSM/LEM.

A special logic is needed for the RCS jet control during LEM backup of the SPS. This logic is very simple. It is based on simply computing the urgencies (which may be zero) to rotate about the y and z axes. The axis associated with the greatest (and non-zero) urgency receives control torque for an entire control sample period. Jet failures are taken into account and if a four jet couple cannot be applied, a two-jet couple is used.

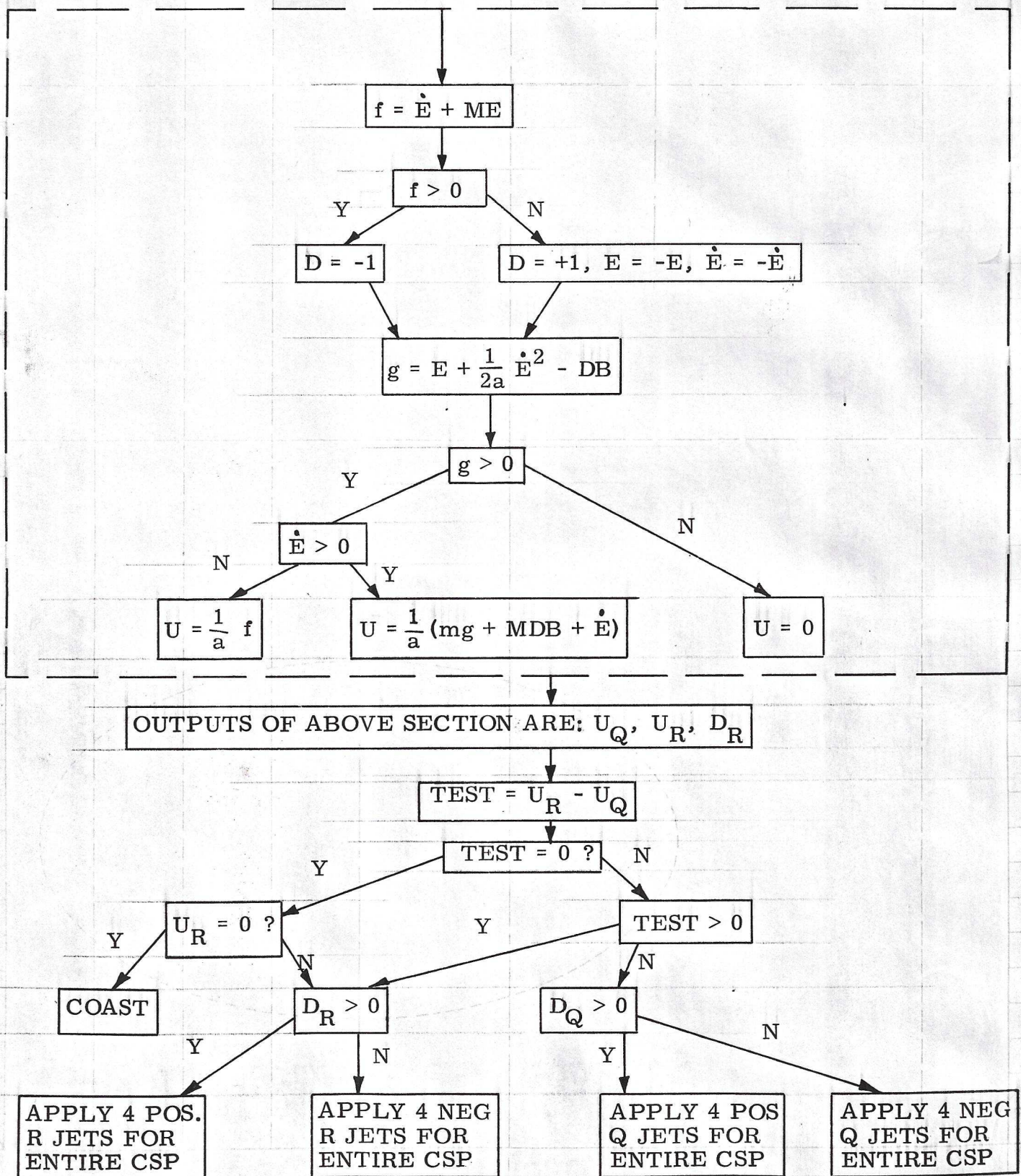
Figure 3-28 is a diagram of the logic which selects the axis and direction of rotation required. Figure 3-29 illustrates the phase plane switching curves on which Figure 3-28 is based.

The parameters which can be adjusted to secure satisfactory behavior are:

1. m ; the slope of the straight line in Fig. 3-29.
(Decreasing m makes the rigid body response slower.)
2. DB ; in Fig. 3-29. (Increasing DB decreases jet firing frequency.)
3. a ; the acceleration of the parabola in Fig. 3-29. (Decreasing a from the nominal acceleration due to the jets increases the rate damping and tends to stabilize the bending mode.)
4. The factor in the definition of K in the trim gimbal control law on page 3-48 (The presently used factor is 0.3. Decreasing this factor tends to stabilize the trim gimbal.)

SPS BACKUP RCS CONTROL LOGIC

SECTION BELOW IS FIRST ENTERED FOR Q AXIS COMPUTATIONS WITH INPUTS $E_Q, \dot{E}_Q, A_Q, M_Q, DB_Q$ IT IS THEN ENTERED FOR R AXIS COMPUTATIONS WITH INPUTS $E_R, \dot{E}_R, A_R, M_R, DB_R$.



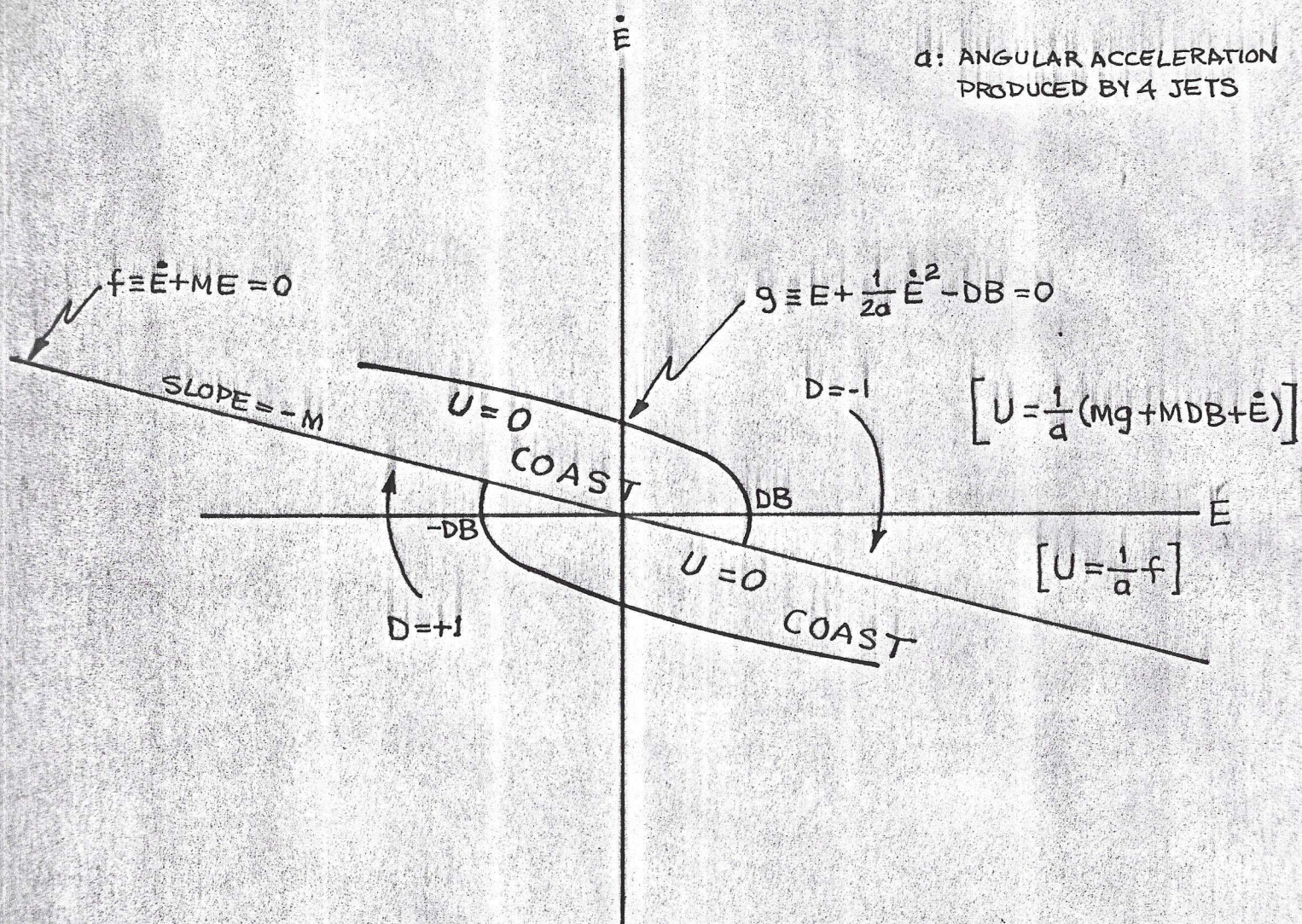


Fig. 3-29 Urgency Function Diagram.

5. The factor w (or K) in the rate derivation equations in section 3.3.8. (Decreasing w lowers the frequency response of the rate derivation filter and tends to reject the bending mode frequencies.)

The RCS jets are used during the SPS burn as they are during the LEM DAP burn phases. (That is, the jets are used only if the trim gimbal does not keep the altitude error inside a bound.) The RCS jets are also used to orient the LEM/CSM prior to engine ignition.

3.4 Digital Uplink to LGC

By means of the LGC UPLINK, the ground can insert data or instruct the LGC in the same manner normally performed by the crew using the DSKY Keyboard. The LGC will be programmed to accept the following UPLINK inputs:

- (1) State Vector Update - LEM
- (2) State Vector Update - CSM
- (3) External Delta - V

Operational procedures governing the use of these Uplink inputs must be developed to ensure proper operation within program constraints.

All information received by the LGC from the Uplink is in the form of keyboard characters. Each character transmitted to the LGC is triply redundant. Thus, if C is the 5-bit character code, then the 16-bit message has the form:

$$1 C \bar{C} C$$

when \bar{C} denotes the bit-by-bit complement of C. To these 16 bits of information the ground adds a 3-bit code specifying which system aboard the spacecraft is to be the final recipient of the data and a 3-bit code indicating which spacecraft should receive the information. The 22 total bits are sub-bit encoded (replacing each bit with a 5-bit code for transmission.) If the message is received and successfully decoded, the receiver onboard will send back an 8-bit "message accepted pulse" to the ground and shift the original 16 bits to the LGC ($1 C \bar{C} C$).

All X's, T's, and P's in the latter part of this section represent one uplink word. Table 3-1 gives the 16 bit codes ($1 C \bar{C} C$) for all keycodes. Unless otherwise specified, all loads are in octal. Scale factors will be included in addenda to this document as they become available.

3.4.1 State Vector Update - LEM

To update the LEM state vector via the uplink the ground should send Verb 70 Enter followed by the parameters listed below, in the order given below.

<u>octal identifier</u>		
1	XXXXXX Enter	(most sig. part of X component of Pos.)
2	XXXXXX Enter	(least sig. part of X component of Pos.)
3	XXXXXX Enter	(most sig. part of Y component of Pos.)
4	XXXXXX Enter	(least sig. part of Y component of Pos.)
5	XXXXXX Enter	(most sig. part of Z component of Pos.)
6	XXXXXX Enter	(least sig. part of Z component of Pos.)
7	XXXXXX Enter	(most sig. part of X component of Vel.)

3.4 Digital Uplink to AGC

By means of the LGC UPLINK, the ground can insert data or instruct the LGC in the same manner normally performed by the crew using the DSKY Keyboard. The LGC will be programmed to accept the following UPLINK inputs:

- (1) LGC Clock Alignment
- (2) Guidance Reference Release
- (3) DFI TLM Calibrate
- (4) Single LGC - LMP Command
- (5) Change of Mission Timer (see Sec. 4.1)
- (6) Change of Mission Phase Register (see Sec. 4.1)
- (7) Change of Mission Timer and Mission Phase Register (see Sec. 4.1)
- (8) Function Inhibit/Enable
- (9) Mission Idle Command
- (10) Update for Burns
- (11) State Vector Update

Operational procedures governing the use of these Uplink inputs must be developed to ensure proper operation within program constraints.

All information received by the LGC from the Uplink is in the form of keyboard characters. Each character transmitted to the LGC is triply redundant. Thus, if C is the 5-bit character code, then the 16-bit message has the form:

1 $C\bar{C}\bar{C}$

where \bar{C} denotes the bit-by-bit complement of C. To these 16 bits of information the ground adds a 3-bit code specifying which system aboard the spacecraft is to be the final recipient of the data and a 3-bit code indicating which spacecraft should receive the information. The 22 total bits are sub-bit encoded (replacing each bit with a 5-bit code for transmission.) If the message is received and successfully decoded, the receiver onboard will send back an 8-bit "message accepted pulse" to the ground and shift the original 16 bits to the LGC (1 $C\bar{C}\bar{C}$).

All X's, T's, and P's in the latter part of this section represent one uplink word. Table 3-1 gives the 16 bit codes (1 $C\bar{C}\bar{C}$) for all keycodes. Unless otherwise specified, all loads are in octal. Scale factors will be included in late revisions to this document as they become available.

3.4.1 LGC CLOCK ALIGN

To align the LGC clock two procedures are required. To set the LGC Clock to a specific value, the ground should send Verb 21, Noun 16 Enter. This must be followed by \pm XXXXX ENTER where each X represents one decimal digit, and the total number represents the time in C.S. that will be set

TABLE 3-1

<u>Character</u>	<u>Uplink Word</u>
0	1 10000 01111 10000
1	1 00001 11110 00001
2	1 00010 11101 00010
3	1 00011 11100 00011
4	1 00100 11011 00100
5	1 00101 11010 00101
6	1 00110 11001 00110
7	1 00111 11000 00111
8	1 01000 10111 01000
9	1 01001 10110 01001
VERB	1 10001 01110 10001
NOUN	1 11111 00000 11111
ENTER	1 11100 00011 11100
ERROR RESET	1 10010 01101 10010
CLEAR	1 11110 00001 11110
KEY RELEASE	1 11001 00110 11001
+	1 11010 00101 11010
-	1 11011 00100 11011

NOTE: It is good operational procedure to end every uplink message with a KEY RELEASE.

octal
identifier

10 ₈	XXXXXX Enter	(least sig. part of X component of Vel.)
11 ₈	XXXXXX Enter	(most sig. part of Y component of Vel.)
12 ₈	XXXXXX Enter	(least sig. part of Y component of Vel.)
13 ₈	XXXXXX Enter	(most sig. part of Z component of Vel.)
14 ₈	XXXXXX Enter	(least sig. part of Z component of Vel.)
15 ₈	XXXXXX Enter	(most sig. part of time)
16 ₈	XXXXXX Enter	(least sig. part of time)

After the enter associated with the last component of any load the ground will verify via downlink that the contents of the special buffer registers are correct. If the load is verified as correct the ground should send a Verb 33 Enter and the LGC will accept the load for computation. If the contents of one or more registers are found in error, however, the ground may either terminate the load by sending Verb 34 Enter or it may choose to correct the registers one at a time. To correct a single register after the enter associated with the last parameter to be loaded, the ground should send XX Enter XXXXX Enter. Where the first two X's are the octal identifier of the parameter and the next 5 X's are the correct contents of the registers. This procedure may be repeated any number of times until all registers contain the desired values. After correcting the registers required, the ground should send Verb 33 Enter and the LGC will accept the load for computation.

3.4.2 State Vector Update - CSM

To update the CSM state vector via the uplink the ground should send Verb 76 Enter and then enter the parameters in a manner identical to that described for LEM updates in Section 3.4.1.

3.4.3 External Delta - V

To load the LGC for an External Delta - V maneuver the ground should send Verb 72 Enter followed by the parameters listed below, in the order given below.

octal
identifier

1	XXXXXX Enter	(most sig. part of T_{ign})
2	XXXXXX Enter	(least sig. part of T_{ign})
3	XXXXXX Enter	(most sig. part of X component of V_g)
4	XXXXXX Enter	(least sig. part of X component of V_g)
5	XXXXXX Enter	(most sig. part of Y component of V_g)

octal
identifier

6	XXXXXX Enter	(least sig. part of Y component of V_g)
7	XXXXXX Enter	(most sig. part of Z component of V_g)
10 ₈	XXXXXX Enter	(least sig. part of Z component of V_g)

The ground should use the same procedure for correcting, terminating or accepting this data as outlined for Verb 70 above.

3.5 LGC Digital Downlink

The LGC digital downlink is only transmitted during high bit rate from the LEM. The LGC digital downlink consists of 50 words per second. Each word consists of 33 bits; the first bit is a "word order code" bit, the next 16 bits are the contents of one 16 bit LGC register and the last 16 bits are the contents of another 16 bit LGC register. (Because the PCM telemetry format requires data in multiples of 8-bit words, the LGC downlink program repeats the last 7 bits from the first 16-bit register, after the 33-bit transmission, in order to "fill" the 40-bit downlink allocation.) In this manner the contents of 100 LGC registers are transmitted in one second.

The downlink format is controlled by an LGC program which loads the next 2 registers to be transmitted into channels 34 and 35. This program is entered on an interrupt caused by an "endpulse" from the telemetry system.

The general LGC downlink format is shown in Table 3-2. Each list contains 50 words (i.e., 100 LGC registers). The first word in any list contains the ID and sync registers and has a word order code bit of zero. The ID register marks the beginning of a list and also identifies which list is being transmitted. The sync register always contains the same 16 bits. These bits (000 0001000111111) are used to sync certain remote site downlink processing equipment. The next 12 words (24 registers) may also change for different lists. These twelve words will have word order code bits of one. Since certain data on the downlink are only meaningful when considered in multiregister arrays (i.e. state vectors) and since the programs which compute these arrays are not synchronized with the downlink program, a "snapshot" is taken of these registers so that changes in their values will not occur while these arrays are being transmitted to the ground. The next 26 words (52 registers) will have word order code bits of one and will probably change from list to list. Since both registers of a word are loaded at the same time, no synchronization problems can arise on double precision parameters. The next 6 words (12 registers) have word order code bits of one and transmit the contents of the latching relays in the DSKY. As such they indicate all displays and certain other functions (i.e. G&N mode switching) handled through the latching DSKY relays. All downlink lists will contain DSPTAB registers in this position in the list.

Table 3-2
GENERAL LGC DOWNLINK FORMAT

Word #	Word Order Code	Contents of	
		1st register	2nd register
1	0	ID	sync
2	1	{ "snapshot" data which will probably change with different lists	
↓	↓		
13	1		
14	1	{ data which will probably change with different lists	
↓	↓		
39	1		
40	1	{ DSPTAB registers	
↓	↓		
45	1		
46	1	TIME2	TIME1
47	1	channel 11	channel 12
48	1	channel 13	channel 14
49	1	channel 30	channel 31
50	1	channel 32	channel 33

3.6.2 PCM Telemetry

<u>Identification</u>	<u>Function</u>	<u>Type</u>	<u>Sample Rate/Sec</u>
GG 0001 V	Computer Digital Data	PCMD (OP)	50**
GG 1040 V	+120 VDC PIPA Supply	PCM (OP)	1
GG 1110 V	2.5 VDC Telemetry Bias No. 1	PCM (OP)	1
GG 1111 V	2.5 VDC Telemetry Bias No. 2	PCM (FQ)	1
GG 1201 V	IMU 28 V 800 CPS 1PCT OD, RMS	PCM (OP)	1
GG 1331 V	3.2K 28V Supply	PCM + (OP)	1
GG 1513 X	+28 VDC IMU Stby/off	PCME + (OP)	1
GG 1523 X	+28 VDC LGC Operate	PCME + (OP)	1
GG 2001 V	X PIPA SG Out in Phase	PCM (OP)	50
GG 2021 V	Y PIPA SG Out in Phase	PCM (OP)	50
GG 2041 V	Z PIPA SG Out in Phase	PCM (OP)	50
GG 2107 V	IG Servo Error In Phase	PCM (FQ)	200
GG 2137 V	MG Servo Error In Phase	PCM (FQ)	200
GG 2167 V	OG Servo Error In Phase	PCM (FQ)	200
GG 2112 V	IG 1X Res Out-SINE	PCM + (OP)	10*
GG 2113 V	IG 1X Res Out-COSINE	PCM + (OP)	10*
GG 2142 V	MG 1X Res Out-SINE	PCM + (OP)	10*
GG 2143 V	MG 1X Res Out-COSINE	PCM + (OP)	10*
GG 2172 V	OG 1X Res Out-SINE	PCM + (OP)	10*
GG 2173 V	OG 1X Res Out-COSINE	PCM + (OP)	10*
GG 2121 V	IG 1X Res Out-SINE 11 Deg.	PCM (FQ)	100
GG 2151 V	MG 1X Res Out-SINE 11 Deg.	PCM (FQ)	100
GG 2181 V	OG 1X Res Out-SINE 11 Deg.	PCM (FQ)	100
GG 2110 C	IG Torque Motor Current	PCM (FQ)	100

* If low bit rate (PCM +) is selected in the LEM T/M system the sample rate on these functions is reduced to 11 sec.

** (Refer to Sec. 3.5)

The next downlink word contains the double precision contents of the AGC clock (i.e. TIME1 and TIME2). This word will have a word order code bit of one and will always retain the position indicated in all lists. The last 4 downlink words (8 registers) contain the contents of channels 11, 12, 13, 14, 30, 31, 32 and 33 in that order. These channels have similar functions to the in and out registers for the Block I computer. Therefore, they will contain the status of a number of discrete interfaces of the LGC. These 4 words will have word order bits of one and will be in the same position on all downlink lists.

More detailed information will be included as addenda to this document as it becomes available.

3.6 Analog Data Telemetry and Recording

3.6.1 Types

The inflight information from the LEM G&N system is of four types:

- (a) PCM telemetry of the LGC Digital Downlink (described in Section 3.5);
- (b) PCM telemetry of OPERATIONAL (required for all LEM missions) analog measurements, which include the following categories:
 - (1) PCM Pulse-code-modulated analog measurements digitally coded into 8-bit words and transmitted at the normal (51.2 k-c) operational bit rate.
 - (2) PCM+ Flight-critical PCM measurements, which continue to be monitored when the PCM is operated in the "slow-format" mode of 1.6 KC.
 - (3) PCME PCM monitor of discrete events (1 bit per word).
 - (4) PCME+ Flight critical PCME measurements monitored in "slow-format" mode;
- (c) PCM telemetry of FLIGHT QUALIFICATION measurements which is discontinued after the flight qualification requirements are fulfilled;
- (d) DFI telemetry of FLIGHT QUALIFICATION measurements.

3.6.2 Authority

The PCM telemetry and DFI telemetry allocations have been defined by NASA in GAEC document LED 360-22- Revision E; 11 April 1966, LEM1-3 Measurement List. The G&N measurements are listed below.

3.6.3 OPERATIONAL PCM Measurements

<u>Measurement #</u>	<u>Description</u>	<u>T/M</u>	<u>Response S/S</u>
GG 0001V	Computer Digital Data 40 Bits	PCMD	50
GG 1040V	+120 VDC PIPA Supply-DC Level	PCM	1
GG 1110V	2.5VDC Telemetry Bias No.1 PCM	PCM	1
GG 1201V	IMU 28V 800CPS 1 PCT 0 Deg. RMS	PCM	1
GG 1331V	3.2KC 28V Supply 1 PCT	PCM+	1/1
GG 1513X	+28 VDC IMU STBY/Off	PCME	1
GG 1523X	+28 VDC LGC Operate	PCME+	1/1
GG 2001V	X PIPA S. G. Out In Phase	PCM	50
GG 2021V	Y PIPA S. G. Out In Phase	PCM	50
GG 2041V	Z PIPA S. G. Out In Phase	PCM	50
*GG 2107V	IG Servo Error In Phase	PCM	100
GG 2112V	IG 1X Res Out-SINE	PCM+	10/1
GG 2113V	IG 1X Res Out-COSINE	PCM+	10/1
*GG 2137V	MG Servo Error In Phase	PCM	100
GG 2142V	MG 1X Res Out-SINE	PCM+	10/1
GG 2143V	MG 1X Res Out-COSINE	PCM+	10/1
*GG 2167V	OG Servo Error In Phase	PCM	100
GG 2172V	OG 1X Res Out-SINE	PCM+	10/1
GG 2173V	OG 1X Res Out-COSINE	PCM+	10/1
GG 2219V	Pitch Att. Error-CDU DAC Out	PCM	10
GG 2249V	Yaw Att. Error-CDU DAC Out	PCM	10
GG 2279V	Roll Att. Error-CDU DAC Out	PCM	10
GG 2300T	PIPA Temperature	PCM+	1/1
GG 3304V	RR Shaft 1X Res. Out-SINE	PCM	10
GG 3305V	RR Shaft 1X Res. Out-COSINE	PCM	10
GG 3324V	RR Trun. 1X Res. Out-SINE	PCM	10
GG 3325V	RR Trun. 1X Res. Out-COSINE	PCM	10
GG 9001X	LGC Warning	PCME+	1/1
GG 9002X	ISS Warning	PCME+	1/1
GG 9003X	PNGS Caution	PCME+	1/1

* NOTE also that for LEM 1, 2, and 3, the sample rates for OPERATIONAL measurement 2107, 2137, and 2167 are increased from 100 S/S to 200 S/S.

3.6.4 FLIGHT QUALIFICATION PCM Measurement for LEMS 1, 2, and 3*

<u>Measurement #</u>	<u>Description</u>	<u>T/M</u>	<u>Response S/S</u>
GG 2110C	IG Torque Motor Current	PCM	100 <i>sm</i>
GG 2121V	IG 1X Res. Out-SINE 11 Deg.	PCM	100 ✓
GG 2140C	MG Torque Motor Current	PCM	100
GG 2151V	MG 1X Res. Out-SINE 11 Deg.	PCM	100 ✓
GG 2170C	OG Torque Motor Current	PCM	100 <i>sm</i>
GG 2181V	OG 1X Res. Out-SINE 11 Deg.	PCM	100 ✓
GG 2301T	IRIG Temperature	PCM	1
GG 6020T	PIPA Calibration Mod. Temp.	PCM	1 60/0000

3.6.5 DFI Telemetry FLIGHT QUALIFICATION Measurements for LEMS 1, 2, and 3.

<u>Measurement #</u>	<u>Description</u>	<u>Recoverable CPS</u>
GG 1111V	2.5 VDC Telemetry Bias No. 2 DFI	1
GG 2220V	IG CDU Fine Error	80
GG 2250V	MG CDU Fine Error	2
GG 2280V	OG CDU Fine Error	2
GG 2302X	IMU Heater Current On	E
GG 3311V	RR Shaft CDU Fine Error	2
GG 3321V	RR Trun. CDU Fine Error	2
GG 6001D	Vibration, Nav. Base Roll	2KC
GG 6002D	Vibration, Nav. Base Pitch	2KC
GG 6003D	Vibration, Nav. Base Yaw	2KC

* NOTE also that for LEMS 1, 2, and 3, the sample rates for OPERATIONAL measurement 2107, 2137, and 2167 are increased from 100 S/S to 200 S/S.