

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Silver

APOLLO

GUIDANCE, NAVIGATION AND CONTROL

G.L. *Silver*
E-2448

USERS' GUIDE TO APOLLO GN&CS
MAJOR MODES AND ROUTINES

FEBRUARY 1970

MIT

**CHARLES STARK DRAPER
LABORATORY**

CAMBRIDGE MASSACHUSETTS 02139

APOLLO

GUIDANCE, NAVIGATION AND CONTROL

Submitted by: Margaret H. Hamilton Date: 2/26/70
M. H. HAMILTON, DIRECTOR, MISSION PROGRAM DEVEL.
APOLLO GUIDANCE AND NAVIGATION PROGRAM

Approved: R. H. Larson Date: 2-27-70
S. L. COPPS, COLOSSUS PROJECT MANAGER
APOLLO GUIDANCE AND NAVIGATION PROGRAM

Approved: R. H. Larson Date: 2-27-70
R. A. LARSON, LUMINARY PROJECT MANAGER
APOLLO GUIDANCE AND NAVIGATION PROGRAM

Approved: R. H. Battin Date: 2/27/70
R. H. BATTIN, DIRECTOR, MISSION DEVELOPMENT
APOLLO GUIDANCE AND NAVIGATION PROGRAM

Approved: D. G. Hoag Date: 27 Feb 70
D. G. HOAG, DIRECTOR
APOLLO GUIDANCE AND NAVIGATION PROGRAM

Approved: Ralph A. Ragan Date: 27 Feb 70
R. R. RAGAN, DEPUTY DIRECTOR
CHARLES STARK DRAPER LABORATORY

G.L. Silver
E-2448

USERS' GUIDE TO APOLLO GN&CS

MAJOR MODES AND ROUTINES

FEBRUARY 1970

MIT

CAMBRIDGE, MASSACHUSETTS, 02139

**CHARLES STARK DRAPER
LABORATORY**

ACKNOWLEDGEMENT

This report was prepared under DSR Project 55-23870, sponsored by the Manned Spacecraft Center of the National Aeronautics and Space Administration through Contract NAS 9-4065 with the Charles Stark Draper Laboratory, Massachusetts Institute of Technology, Cambridge, Mass.

The publication of this report does not constitute approval by the National Aeronautics and Space Administration of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

The 70's will see the hidden environ-
ments, that cause multitudes of un-
expected changes, pushed up into
full visibility.

Marshal McLuhan

FOREWORD

This document is an attempt to present, in one volume, a comprehensive, user-oriented description of the APOLLO GN&C system. The objective is to comprise all major modes, routines, and extended verbs defined by the Guidance System Operations Plan (GSOP) and to describe their operation, theory, and interrelationships in sufficient detail for a crew member or mission controller to gain the prerequisite understanding on which to base a more rigorous study of specific, flight-particular details and procedures.

Essentially, then, the GN&CS Users' Guide is designed to be system, rather than mission, oriented in that procedural details vary from mission to mission. As a training text defining basic procedures, the Guide will be revised as necessary to remain current; it should not, however, be construed as reflecting the most recent procedures or system configuration. For specific information regarding a particular mission, refer to the appropriate MSC-approved Guidance System Operations Plan (GSOP), Crew Procedures Document, Mission Techniques Document, and Crew Checklist.


The Contents lists the sections, subsections, and paragraphs of the completed document. Related illustrations and tables are tabulated after the Contents to permit ready reference. As they are written and complete their review cycle, each subdivision will be printed and forwarded for inclusion. The design of the volume is to group the various major modes and routines under the functional headings: Pre-launch, Boost/Ascent, Coasting Navigation, Targeting, Powered Flight, Alignment, and Entry/Descent. Introductions are now being reviewed that will provide the context and fundamental theory underlying each functional area. The following outline of the Introduction to Coasting Navigation should give a sense of the completed document's organization:

4.1 Introduction to Coasting Navigation (10-15 pages)

4.1.1 Coasting Navigation as Practiced in Three Mission Phases

4.1.1.1 Cislunar

- 4.1.1.2 Rendezvous
- 4.1.1.3 Orbital and Lunar Surface
- 4.1.2 Recursive Navigation: Salient System Properties, Concepts, and Techniques
 - 4.1.2.1 Error Ellipsoid
 - 4.1.2.2 Measurement: Sensor Asymmetry, b vector, Six-dimensional State Vector
 - 4.1.2.3 W-Matrix
 - 4.1.2.4 Kalman Filter
- 4.1.3 Special Considerations for Each Mission Phase
 - 4.1.3.1 Cislunar
 - 4.1.3.2 Rendezvous
 - 4.1.3.3 Orbital or Lunar Surface



Jack C. Reed
APOLLO Documentation Group

CONTENTS

<u>Section</u>	<u>Page</u>
1.0 INTRODUCTION	
2.0 PRELAUNCH	
2.1 Introduction	
2.2 Command Module Computer (CMC)	
2.2.1 P00, CMC Idling	
2.2.2 P01, Initialization	
2.2.3 P02, Gyrocompassing	
2.2.4 P03, Optical Verification of Gyrocompassing	
2.2.5 P06, CMC Power Down	
2.3 Lunar Module Guidance Computer (LGC)	
2.3.1 P00, LGC Idling	
2.3.2 P06, LGC Power Down	
3.0 BOOST/ ASCENT	
3.1 Introduction	
3.2 Command Module Computer	
3.2.1 P11, Earth-orbit-insertion Monitor	
3.3 Lunar Module Guidance Computer	
3.3.1 P12, Nominal Ascent	
3.3.2 P70, Descent Propulsion System Abort	
3.3.3 P71, Ascent Propulsion System Abort	
4.0 COASTING NAVIGATION	
4.1 Introduction	
4.2 Command Module Computer	

CONTENTS

<u>Section</u>	<u>Page</u>
*4.2.1 P20, Rendezvous Navigation	4.2.1-1
*4.2.2 P21, Ground-track Determination	4.2.2-1
*4.2.3 P22, Orbital Navigation	4.2.3-1
*4.2.4 P23, Cislunar Midcourse Navigation	4.2.4-1
4.2.5 P27, CMC Update	
4.3 Lunar Module Guidance Computer	
4.3.1 P20, Rendezvous Navigation	
4.3.2 P21, Ground-track Determination	
4.3.3 P22, Lunar-surface Navigation	
4.3.4 P25, Preferred Tracking Attitude	
4.3.5 P27, LGC Update	
5.0 TARGETING	
5.1 Introduction	
5.2 Command Module Computer	
*5.2.1 P30, External Δv	5.2.1-1
*5.2.2 P32, Co-elliptic Sequence Initiation (CSI)	5.2.2-1
*5.2.3 P33, Constant Delta Altitude (CDH)	5.2.3-1
*5.2.4 P34, Transfer-phase Initiation (TPI)	5.2.4-1
*5.2.5 P35, Transfer-phase Midcourse	5.2.5-1
*5.2.6 P37, Return to Earth	5.2.6-1
5.2.7 R36, Rendezvous-out-of-Plane Display	
5.2.8 P72, LM Co-elliptic Sequence Initiation	
5.2.9 P73, LM Constant Delta Altitude	
5.2.10 P74, LM Transfer Phase Initiation	
5.2.11 P75, LM Transfer Phase Midcourse	
5.2.12 P76, Target Δv	
5.3 Lunar Module Guidance Computer	
5.3.1 P30, External Δv	
5.3.2 P32, Co-elliptic Sequence Initiation (CSI)	

* Indicates sections currently enclosed.

CONTENTS

<u>Section</u>	<u>Page</u>
5.3.3 P33, Constant Delta Altitude (CDH)	
5.3.4 P34, Transfer-phase Initiation (TPI)	
5.3.5 P35, Transfer-phase Midcourse	
5.3.6 P72, CSM Co-elliptic Sequence Initiation	
5.3.7 P73, CSM Constant Delta Altitude	
5.3.8 P74, CSM Transfer Phase Initiation	
5.3.9 P75, CSM Transfer Phase Midcourse	
5.3.10 P76, Target Δv	
 6.0 POWERED FLIGHT	
6.1 Introduction	
6.2 Command Module Computer	
*6.2.1 P40, Service Propulsion System	6.2.1-1
*6.2.2 P41, Reaction Control System	6.2.2-1
*6.2.3 P47, Thrust Monitor	6.2.3-1
 6.3 Lunar Module Guidance Computer	
6.3.1 P40, Descent Propulsion System	
6.3.2 P41, Reaction Control System	
6.3.3 P42, Ascent Propulsion System	
6.3.4 P47, Thrust Monitor	
 7.0 ALIGNMENT	
7.1 Introduction	
7.2 Command Module Computer	
7.2.1 P51, IMU Orientation Determination	
7.2.2 P52, IMU Realign	
7.2.3 P53, Backup IMU Orientation Determination	
7.2.4 P54, Backup IMU Realign	

*Indicates sections currently enclosed.

CONTENTS

<u>Section</u>	<u>Page</u>
7.3 Lunar Module Guidance Computer	
7.3.1 P51, IMU Orientation Determination	
7.3.2 P52, IMU Realign	
*7.3.3 P57, Lunar Surface Align	7.3.3-1
8.0 ENTRY/DESCENT	
8.1 Introduction	
8.2 Command Module Computer (CM ENTRY)	
8.2.1 P61, Entry Preparation	
8.2.2 P62, CM-SM Separation and Pre-entry maneuver	
8.2.3 P63, Initialization	
8.2.4 P64, Post 0.05g	
8.2.5 P65, Upcontrol	
8.2.6 P66, Ballistic	
8.2.7 P67, Final Phase	
8.3 Lunar Module Guidance Computer (LM Descent)	
8.3.1 P63, Braking Phase	
8.3.2 P64, Approach Phase	
8.3.3 P65, Landing Phase (Automatic)	
8.3.4 P66, Landing Phase (ROD)	
8.3.5 P68, Landing Confirmation	
9.0 ADDITIONAL EXTENDED VERBS AND ROUTINES	

* Indicates sections currently enclosed

ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
4.2.1-1	Simplified Rendezvous Navigation Diagram 4.2.1-3
4.2.1-2	Simplified Flow Diagram Showing Relationship of P20 to Other CMC Programs 4.2.1-10
4.2.1-3	Rendezvous Navigation Program (P20) 4.2.1-11
4.2.1-4	IMU Status Check Routine (R02) 4.2.1-13
4.2.1-5	Rendezvous Tracking Data Processing Routine (R22) 4.2.1-14
4.2.1-6	Tracking Attitude Routine (R61) 4.2.1-17
4.2.1-7	Attitude Maneuver Routine (R60) 4.2.1-19
4.2.1-8	Automatic Optics Positioning Routine (R52) (Rendezvous) 4.2.1-21
4.2.1-9	Rendezvous Tracking Sighting Mark Routine (R21) 4.2.1-23
4.2.1-10	Backup Rendezvous Tracking Sighting Mark Routine (R23) 4.2.1-24
4.2.1-11	Rendezvous Parameter Display Routine No. 1 (R31) 4.2.1-25
4.2.1-12	Rendezvous Parameter Display Routine No. 2 (R34) 4.2.1-26
4.2.1-13	Typical Tracking Schedule for a CSM-monitored-LM- active Rendezvous 4.2.1-34
4.2.1-14	Typical RR, δR , δv Updates 4.2.1-36
4.2.1-15	Typical VHF and SXT δR , δv Updates 4.2.1-37
4.2.2-1	Ground Track Determination Program (P21) 4.2.2-3
4.2.3-1	Orbital Navigation Program (P22) 4.2.3-3
4.2.3-2	Landmark Tracking Geometry for a 60-Nautical Mile Circular Lunar Orbit 4.2.3-10
4.2.3-3	SXT and SCT Fields of Coverage 4.2.3-12
4.2.3-4	Tracking Geometry for Mode I Landmark Tracking 4.2.3-13
4.2.3-5	Tracking Geometry for Mode III Undocked Landmark Tracking 4.2.3-15
4.2.4-1a	Star Horizon Measurement Geometry (Near-Horizon) . . . 4.2.4-2
4.2.4-1b	Star Horizon Measurement Geometry (Far Horizon) 4.2.4-3
4.2.4-2	P23 Activity for G-Mission Translunar and Transearth Trajectories 4.2.4-4
4.2.4-3	Available Measurement Stars Visible in SCT FOV at 148:30 GET and 192:30 GET during APOLLO 11 4.2.4-6
4.2.4-4	Cislunar Navigation Program (P23) 4.2.4-14

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
4.2.4-5	Optics Calibration Routine (R57)	4.2.4-17
4.2.4-6	APOLLO 8 Translunar Midcourse Navigation	4.2.4-24
4.2.4-7	Correct Reticle Alignment with Substellar Tangent for Marktaking	4.2.4-26
5.2.1-1	External Δv Program (P30)	5.2.1-2
5.2.2-1	An Example of a CSM-active Rendezvous Configuration	5.2.2-2
5.2.2-2	Coelliptic Sequence Initiation (CSI) (P32)	5.2.2-4
5.2.3-1	Constant Delta Attitude (CDH) Program (P33)	5.2.3-4
5.2.3-2	Alarm Code 00611 Conditions and Crew Actions	5.2.3-12
5.2.4-1	Transfer Phase Initiation Program (P34)	5.2.4-4
5.2.5-1	Transfer Phase Midcourse Program (P35)	5.2.5-3
5.2.6-1	Typical Abort Trajectories for TLI+6 Hours	5.2.6-2
5.2.6-2	Typical Abort Trajectories for TLI+20 Hours	5.2.6-3
5.2.6-3	Typical Abort Trajectories for TLI+50 Hours	5.2.6-4
5.2.6-4	Return to Earth Program (P37)	5.2.6-7
5.2.6-5	Relationship of Δv to Desired Flight-path Angle at Earth Entry: Returns from Near-circular Earth Orbits of Several Altitudes	5.2.6-9
5.2.6-6	Minimum Fuel Requirements During Translunar Coast	5.2.6-11
5.2.6-7	Range from Entry Interface (400,000 ft) to Landing	5.2.6-13
5.2.6-8	Locus of Available Solutions for Four Typical Pre- maneuver State Vectors	5.2.6-14
5.2.6-9	Relationship of Return-flight Duration to Desired Flight-path Angle at Earth Entry: Returns from Near- circular Earth Orbits of Several Altitudes (with Negative Pre- maneuver Flight-path Angles)	5.2.6-15
5.2.6-10	Correlation of Conic and Precision Solutions for Longitude: Returns from Translunar Coast	5.2.6-17
5.2.6-11	Approximate Relationship of Precision-phase Running Time versus Return-flight Duration	5.2.6-18
5.2.6-12	Relationship of Δv_D to Time of Flight (t_{21}) During Translunar Coast	5.2.6-20
5.2.6-13	Sensitivity of Landing-site Longitude to Changes in Δv_D : Returns from Translunar Coast	5.2.6-23
5.2.6-14a	Increase in Δv_D to Produce a Desired Increase in LONG: $K = 0.04$ to 0.004	5.2.6-24
5.2.6-14b	Increase in Δv_D to Produce a Desired Increase in LONG: $K = 0.4$ to 0.04	5.2.6-25

ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
5.2.6-15	Area, Near Lunar Sphere of Influence, Where P37 Will Not Converge to a Precision Solution 5.2.6-29
5.2.6-16	Pre-maneuver Conditions Where a Possible Discontinuity Exists in the Relationship Between Δv and Transfer Time 5.2.6-31
6.2.1-1	SPS Maneuver Program (P40) 6.2.1-5
6.2.1-2	Time Lines of SPS Maneuver Program (P40) 6.2.1-12
6.2.1-3	SPS Thrust Fail Routine (R40) 6.2.1-16
6.2.1-4	State Vector Integration Routine (R41) 6.2.1-17
6.2.2-1	RCS Maneuver Program (P41) 6.2.2-5
6.2.2-2	Time Lines of RCS Maneuver Program (P41) 6.2.2-9
6.2.3-1	Thrust Monitor Program (P47) 6.2.3-4
6.2.3-2	Time Lines of Thrust Monitor Program (P47) 6.2.3-6
7.3.3-1	Lunar Surface Alignment Program (P57) 7.3.3-7
7.3.3-2	Sighting Data Display Routine (R54) 7.3.3-15
7.3.3-3	Lunar Surface Sighting Mark Routine (R59) 7.3.3-16
7.3.3-4	Sighting Mark Routine (R53) 7.3.3-19
7.3.3-5	Alignment Optical Telescope Reticle Pattern 7.3.3-22
7.3.3-6	Markrupt Routine (R57) 7.3.3-23
7.3.3-7	Celestial Body Definition Routine (R58) 7.3.3-28

TABLES

<u>Table</u>	<u>Page</u>
4.2.1-I	Regular Verbs and DSKY Displays Associated with Rendezvous Navigation (P20) 4.2.1-5
4.2.1-II	Extended Verbs Used with Rendezvous Navigation 4.2.1-7
4.2.2-I	P21 Ground Track Determination Procedures 4.2.2-2
4.2.3-I	Purposes of Orbital Navigation 4.2.3-1
4.2.3-II	P22 Procedures 4.2.3-7
4.2.4-I	P23 Calibration Procedure 4.2.4-9
4.2.4-II	P23 DSKY Input Output Activity 4.2.4-18
4.2.4-III	Recommended Procedure in Case of Communication Loss 4.2.4-28
5.2.1-I	External Δv Inputs (P30) 5.2.1-3
5.2.1-II	External Δv Outputs (P30) 5.2.1-4
5.2.2-I	P32 Program Inputs 5.2.2-7
5.2.2-II	P32 Program Outputs 5.2.2-10
5.2.3-I	P33 Input 5.2.3-7
5.2.3-II	P33 Output 5.2.3-8
5.2.3-III	Alarm Recovery Summary 5.2.3-13
5.2.4-I	P34 Input 5.2.4-7
5.2.4-II	P34 Output 5.2.4-8
5.2.5-I	P35 Input 5.2.5-5
5.2.5-II	P35 Output 5.2.5-6
5.2.6-I	P37 Crew Inputs and Program Outputs 5.2.6-5
5.2.6-II	Entry Range and Octal Equivalent Loaded in P37RANGE . 5.2.6-12
6.2.1-I	Displays Associated with P40 6.2.1-3
6.2.1-II	Extended Verbs for Use with P40 6.2.1-4
6.2.2-I	Displays Associated with P41 6.2.2-3
6.2.2-II	Extended Verbs for Use with P41 6.2.2-4
6.2.3-I	Displays Associated with P47 6.2.3-2
6.2.3-II	Extended Verbs for Use with P47 6.2.3-3
7.3.3-I	Program Displays 7.3.3-2
7.3.3-II	Sources of IMU Alignment Vectors in P57 7.3.3-13

4.2.1 P20, Rendezvous Navigation—CMC

The Rendezvous Navigation Program (P20) is an onboard means of updating either of two state vectors (CSM or LM) carried in the Command Module Computer. The designated state vector is updated by incorporating measurements of line of sight (optics) and range (VHF) from the CSM to the LM. Except during the thrusting phases, P20 operates continuously throughout CSM-LM rendezvous, regardless of which is the active vehicle. For a CSM-active rendezvous, P20 operates in conjunction with whichever is appropriate of the following targeting programs, as determined by rendezvous profile:

- P30—External Δv
- P32—Co-elliptic Sequence Initiation (CSI)
- P33—Constant Delta Altitude (CDH)
- P34—Transfer Phase Initiation (TPI)
- P35—Transfer Phase Midcourse (TPM)

For an LM-active, CSM-monitored rendezvous, P20 operates in conjunction with whichever is appropriate of the following targeting programs, again as determined by the rendezvous profile:

- P72—LM Co-elliptic Sequence Initiation
- P73—LM Constant Delta Altitude
- P74—LM Transfer Phase Initiation
- P75—LM Transfer Phase Midcourse
- P76—Target Δv

Essentially, P20 provides the targeting programs with a continually updated state vector for one vehicle with respect to the current state-vector estimate for the other. The appropriate targeting program, in turn, computes the Δv required to effect rendezvous.

Figure 4.2.1-1 is a simplified functional diagram of the logic for updating one of the two CMC state vectors—designated in Figure 4.2.1-1 as "passive vehicle orbit" and "active vehicle orbit."

Extrapolating both state vectors to the time of measurement, P20 computes an estimated tracking quantity (\hat{Q}), which is compared with a measured tracking quantity (Q) to obtain a measurement deviation δQ . This is multiplied by a statistical weighting vector (\underline{w}) comprising state-vector uncertainties, sensor performance (α^2), and sensor geometry vector (\underline{b}). The resulting $\delta \underline{x}$ is a statistically optimum linear estimate of deviation to be added to the current estimate of the state vector selected to be updated.

Typically, tracking data are processed once every minute (for VHF marks, as often as every 20 sec for optics), and the selected state vector is automatically updated by the computed deviation $\delta \underline{x}$. If the magnitude of either the position-vector change ($\delta \underline{r}$) or the velocity-vector change ($\delta \underline{v}$) is not less than preset values, however, the crew is alerted by a special display, and the update occurs only upon crew command, after verifying the tracking data.

4.2.1.1 Crew Options

The fundamental crew option is whether to update the CSM state vector or the LM state vector. Considerations affecting the decision are (1) the desire to update the state vector having the largest uncertainties, and (2) a desire to update the state vector of the vehicle that is to perform the rendezvous maneuver. Ordinarily, both considerations will favor updating the LM. Should the LM state-vector uncertainty be the smaller, however, updating the CSM would probably be preferred.

The second option regards the selection of sensors to be used in taking measurements. Ordinarily, the CSM optics will be used in conjunction with the VHF range link. If both sensor systems are not operational, however, or if, for example, the LM is not visible, P20 can be performed, with degraded accuracy, using only one of the sensors.

The third option is whether to use the preferred tracking attitude (sextant tracking) or the backup X-axis tracking attitude (COAS tracking). The "preferred" is the normal procedure.

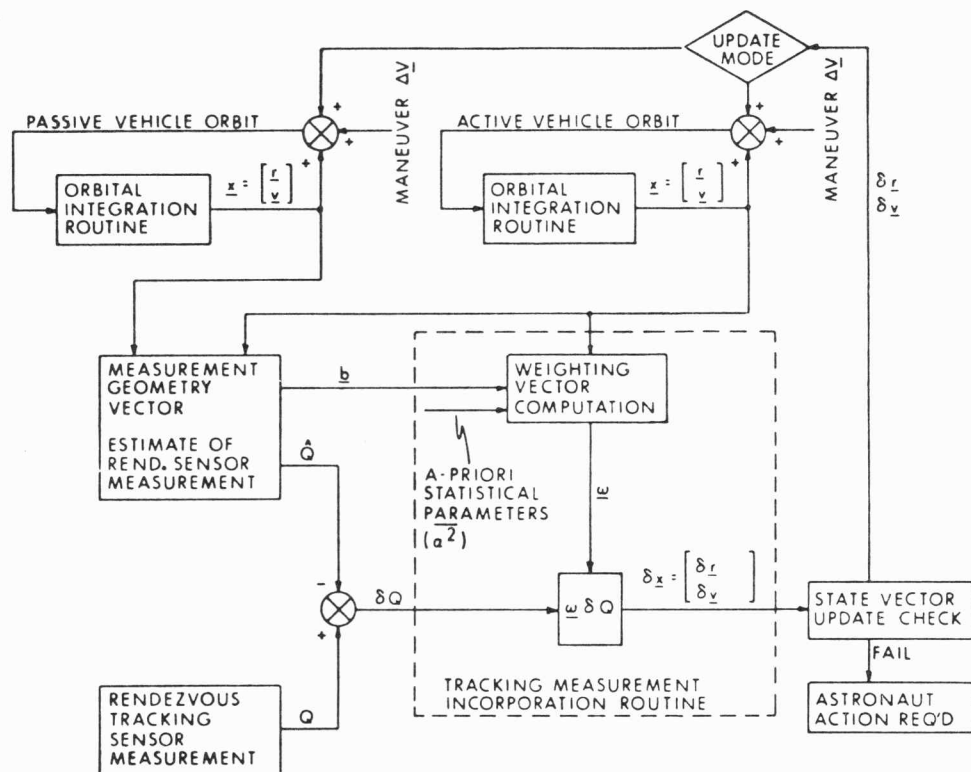


Figure 4.2.1-1. Simplified Rendezvous Navigation Diagram

A fourth option is whether to manually perform the attitude maneuver to acquire the LM in the sextant field or to allow the RCS DAP to perform the maneuver automatically. This option will be described more fully when the Attitude Maneuver Routine (R60) is introduced as a part of the computation sequence.

4.2.1.2 Computational Sequence

Table 4.2.1-I is a summary of Rendezvous Navigation displays; Table 4.2.1-II gives the extended verbs; and Figures 4.2.1-2 through 4.2.1-12 diagram the relationship of P20 to other programs, its sequence of computation, and its associated routines:

- R02 — The IMU Status Check Routine (Figure 4.2.1-4) is called by programs requiring an aligned IMU. R02 checks the IMU orientation (REFSMMAT) flag and the IMU operate bit and initiates a PROG alarm if either is not set. The crew verifies the alarm by keying VERB 5 NOUN 9 ENTR. If IMU orientation is not known, but the inertial subsystem (ISS) is operating, alarm code 00220 will be displayed; if the ISS is not operating, alarm code 00210 will be displayed. For either alarm, keying RSET sends the program to the Final Automatic Request Terminate Routine (R00), where the crew turns on the ISS (if off) and calls either the primary or backup IMU Orientation Determination Program (P51 or P53).
- R22 — The Rendezvous Tracking Data Processing Routine (Figure 4.2.1-5) is started by P20 and continues to run until P20 is terminated. R22 processes optical and VHF ranging data and updates the state vector designated by the state-vector flag. Incorporation of VHF data is enabled by VERB 87 ENTR and disabled by VERB 88 ENTR.
- R61 The Tracking Attitude Routine (Figure 4.2.1-6) is called either by P20 or R52. R52 calls R61 on every pass during rendezvous tracking. On every fourth pass (only), R61 extrapolates the CSM and LM state vectors to the present, calculates the LOS from the CSM to the LM, and computes the IMU gimbal angles required to keep the CSM properly oriented for tracking the LM. If the PREFERRED-ATTITUDE flag is set (automatically by P20 or by crew's VERB 76 ENTR), an appropriate attitude is held for SXT and VHF tracking; if the PREFERRED-ATTITUDE flag is reset (VERB 77 ENTR), an appropriate attitude is held (+X-axis pointed at LM) for COAS tracking. Comparing the required and present gimbal angles, R61 determines whether the required change in any gimbal angle is more than 10 deg. If all gimbal angles are within 10 deg of required, R61 computes the LOS angular velocity, resolves it into RCS control axes, and generates appropriate input to the RCS DAP.

TABLE 4.2.1-1

REGULAR VERBS AND DSKY DISPLAYS ASSOCIATED WITH RENDEZVOUS NAVIGATION (P20) (SHEET 1 OF 2)

DSKY	Initiated by	Purpose	Condition	Register
V05 N09 E	Astronaut	Verify PROG alarm	00210 = ISS not on 00220 = IMU orientation unknown 00407 = TA > 50 deg 00406 = P20 not in progress	Rn xxxxx
FL V37	R00	Request astronaut to select program	---	---
FL V50 N18	R60	Priority* display of required gimbal angles	OGA (roll) IGA (pitch) MGA (yaw)	R1 xxx.xx deg R2 xxx.xx deg R3 xxx.xx deg
V06 N18	R60	Priority* display of required gimbal angles	OGA IGA MGA	R1 xxx.xx deg R2 xxx.xx deg R3 xxx.xx deg
FL V51	R21	Request "Please Mark"	---	---
FL V06 N94	R23	Display backup (COAS) optics shaft and trunnion angles	00000 = Shaft angle (SA), nominal 57470 = Trunnion angle (TA), nominal	R1 xxx.xx deg R2 xx.xxx deg
V24E	Astronaut	Load desired SA and TA	---	R1 xxx.xx deg R2 xx.xxx deg
FL V53	R23	Perform alternate LOS mark	---	---

* Priority display is an internally generated display that will override any other internally generated display. Display cannot be responded to for 2 seconds.

TABLE 4. 2. 1-I

REGULAR VERBS AND DSKY DISPLAYS ASSOCIATED WITH RENDEZVOUS NAVIGATION (P20) (SHEET 2 OF 2)

DSKY	Initiated by	Purpose	Condition	Register
FL V06 N49	R22	Priority* display of state-vector data for crew approval	ΔR Δv Source code	R1: xxxx. x n. mi. R2: xxxx. x ft/sec R3: 0000x
FL V06 N99	V67	Display W-matrix RMS Error	Position error Velocity error Option code (Rendezvous)	R1: xxxxx. ft R2: xxxx. x ft/sec R3: 00001
V16 N22E	Astronaut	Monitor desired gimbal angles	OGA IGA MGA	R1: xxx. xx deg R2: xxx. xx deg R3: xxx. xx deg
V16 N92E	Astronaut	Monitor desired optics angles	shaft trunnion	R1: xxx. xx deg R2: xx. xxx deg
FL V16 N54	R31	Monitor range data	range range rate theta	R1: xxx. xx n. mi. R2: xxxx. x ft/sec R3: xxx. xx deg
FL V16 N53	R34	Monitor range data	range range rate phi	R1: xxx. xx n. mi. R2: xxxx. x ft/sec R3: xxx. xx deg

TABLE 4.2.1-II

EXTENDED VERBS USED WITH RENDEZVOUS NAVIGATION (SHEET 1 OF 3)

VERB	Identification	Purpose	Remarks
32 ENTR*	Recycle	Reject R22 Update data when displayed by N49	See discussion of excessive update parameters, paragraphs 4.2.1.5.1 - 4.2.1.5.3
44 ENTR 45 ENTR	Set Surface Flag Reset Surface Flag	Indicates LM on lunar surface Indicates LM not on lunar surface	This flag must be in the proper configuration before the Tracking-attitude Routine (R61) is performed.
54 ENTR 57 ENTR	Do R23 Do R21	Perform LM markings using the backup (COAS) optics Perform LM markings using the SXT	With P20 running in the background and with R61 and R52 maintaining attitude and optics positioning (preferred-attitude flag set), the marking routine (R21 or R23) can be called whenever required by the mission marking schedule.
56 ENTR	Reset Rendezvous Flag	Terminate P20 without terminating other major programs	Resetting this flag terminates the entire rendezvous-navigation process. Also, reset by P00 selection (VERB 37 ENTR 00 ENTR). Set by P20 selection.
58 ENTR	Reset Stick Flag and set V50N18 Flag	Allow RCS DAP to resume automatic attitude control, and R61 to call R60 (after initial pass through R61).	The stick flag is set whenever RHC is taken out of detent and the CMC CONT switch is in the CMC position. Once set, the flag can only be reset by a selection of a new Program or by VERB 58 ENTR. The V50N18 Flag is initially set by VERB 37 ENTR 20 ENTR and is reset during each pass through R61. After the initial pass, R61 can call R60 only after the crew's VERB 58 ENTR.
62 ENTR	Select Mode 2	Provide FDAI reference for manual attitude maneuver	Displays total attitude error (NOUN22 - NOUN20) on FDAI error needles

* Though, strictly speaking, Verb 32 is not an extended verb, it is included here for convenience in summarizing special-purpose verbs associated with this program.

TABLE 4.2.1-II

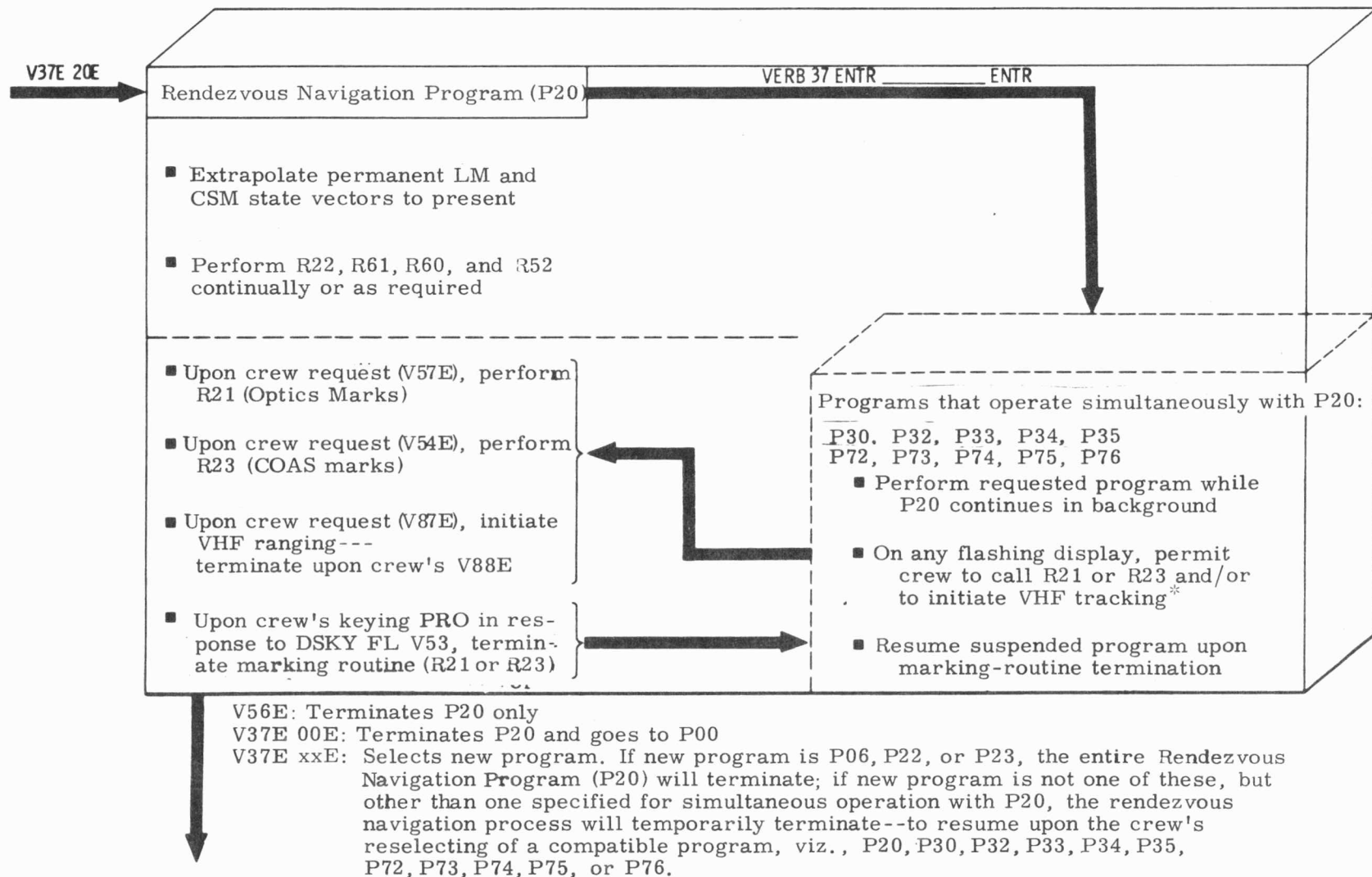
EXTENDED VERBS USED WITH RENDEZVOUS NAVIGATION (SHEET 2 OF 3)

VERB	Identification	Purpose	Remarks
67 ENTR	W-Matrix RMS Display	To display W-Matrix and to provide a means of changing and reinitializing the preset values.	When reinitialization of the W-Matrix to a value other than the preset value is desired, the crew keys VERB 67 ENTR and enters the new values into NOUN 99. The W-Matrix will then reinitialize to the new values when the next mark is incorporated by R22.
76 ENTR	Set Preferred-Attitude Flag	Cause R61 to drive CSM attitude to align SXT LOS with LM	The Preferred-Attitude Flag is automatically set when P20 is entered. Therefore, if +X-axis alignment with LM is desired, VERB 77 ENTR should be keyed before R61 begins the attitude maneuver.
77 ENTR	Reset Preferred-Attitude Flag	Cause R61 to drive CSM attitude to align +X-axis with LM	
80 ENTR	Set State-Vector Flag to LM	Cause the LM state vector to be updated	The State-Vector Flag is automatically set to LM when P20 is entered. Therefore, if the CSM state vector is that intended for update, VERB 81 ENTR must be keyed before the marking routine is called.
81 ENTR	Set State-Vector Flag to CSM	Cause the CSM state vector to be updated	
83 ENTR	Do R31	Display first set of rendezvous parameters	DSKY displays range, range rate, and theta, the angle between local horizontal and the spacecraft X-axis (FL VERB 16 NOUN 54)
85 ENTR	Do R34	Display second set of rendezvous parameters	DSKY displays range, range rate, and phi, the angle between local horizontal and the trunnion SLOS (FL VERB 16 NOUN 53)
86 ENTR	---	Reject R23 mark	Erases sighting data in position 1 and recycles to permit new mark

TABLE 4.2.1-II

EXTENDED VERBS USED WITH RENDEZVOUS NAVIGATION (SHEET 3 OF 3)

VERB	Identification	Purpose	Remarks
87 ENTR	Set VHF Range Flag	Allow R22 to accept range data	This flag is <u>not</u> set automatically. Therefore, if VHF range data are to be incorporated in the state-vector update, VERB 87 ENTR must be keyed.
88 ENTR	Reset VHF Flag	Stops R22 from accepting range data	VHF ranging will then continue automatically until the crew either keys VERB 88 ENTR or any VERB 37.
93 ENTR	Reset RENDWFLAG	Reinitialize W-Matrix	If reinitializing without changing the preset values, the crew need only key VERB 93 ENTR.



*Navigation data are not incorporated, however, during the time that UPDATE flag is reset. See paragraph 4.2.1.5.

Figure 4.2.1-2, Simplified Flow Diagram Showing Relationship of P20 to Other CMC Programs

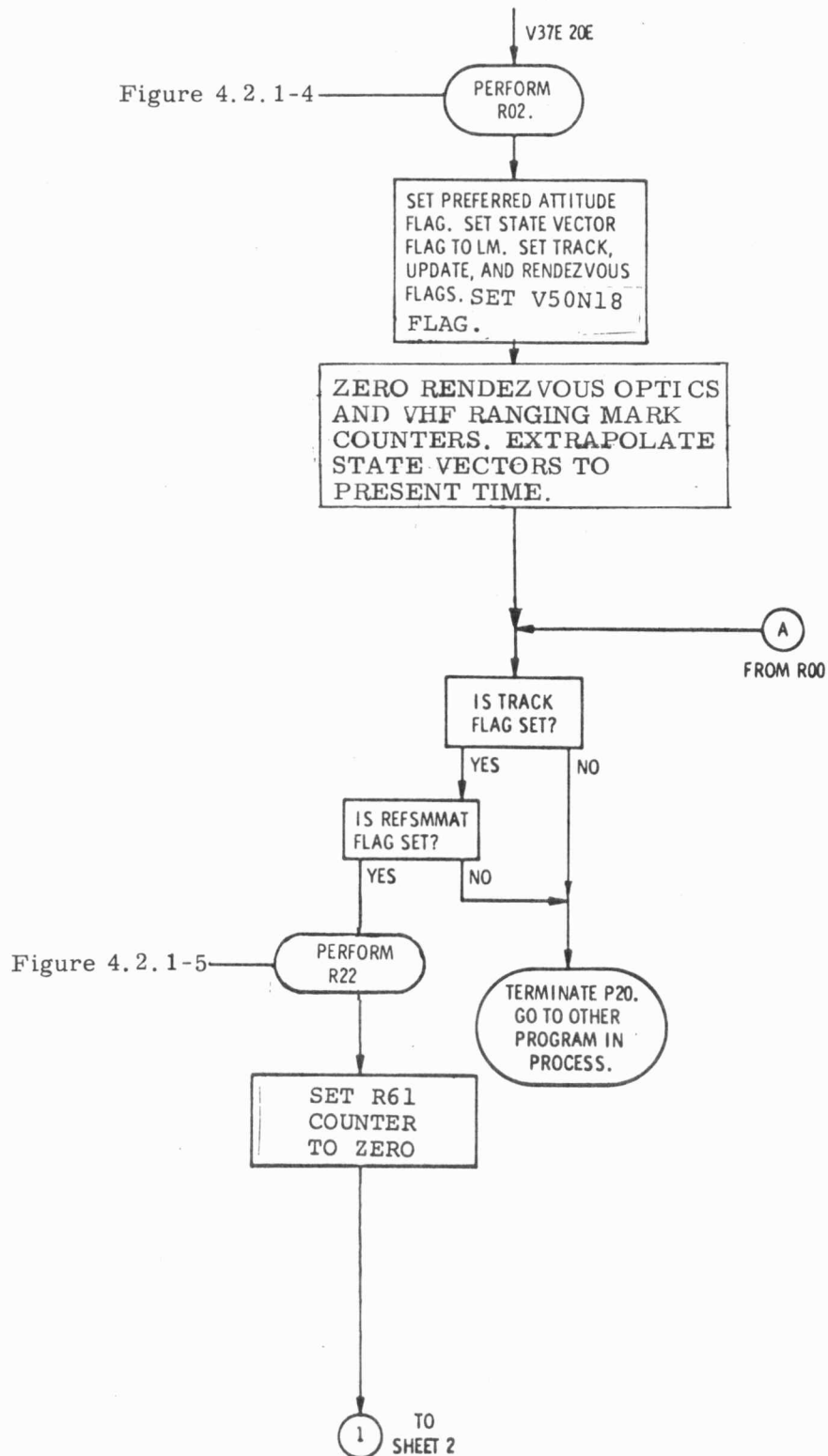


Figure 4.2.1-3 Rendezvous Navigation Program (P20) (Sheet 1 of 2)

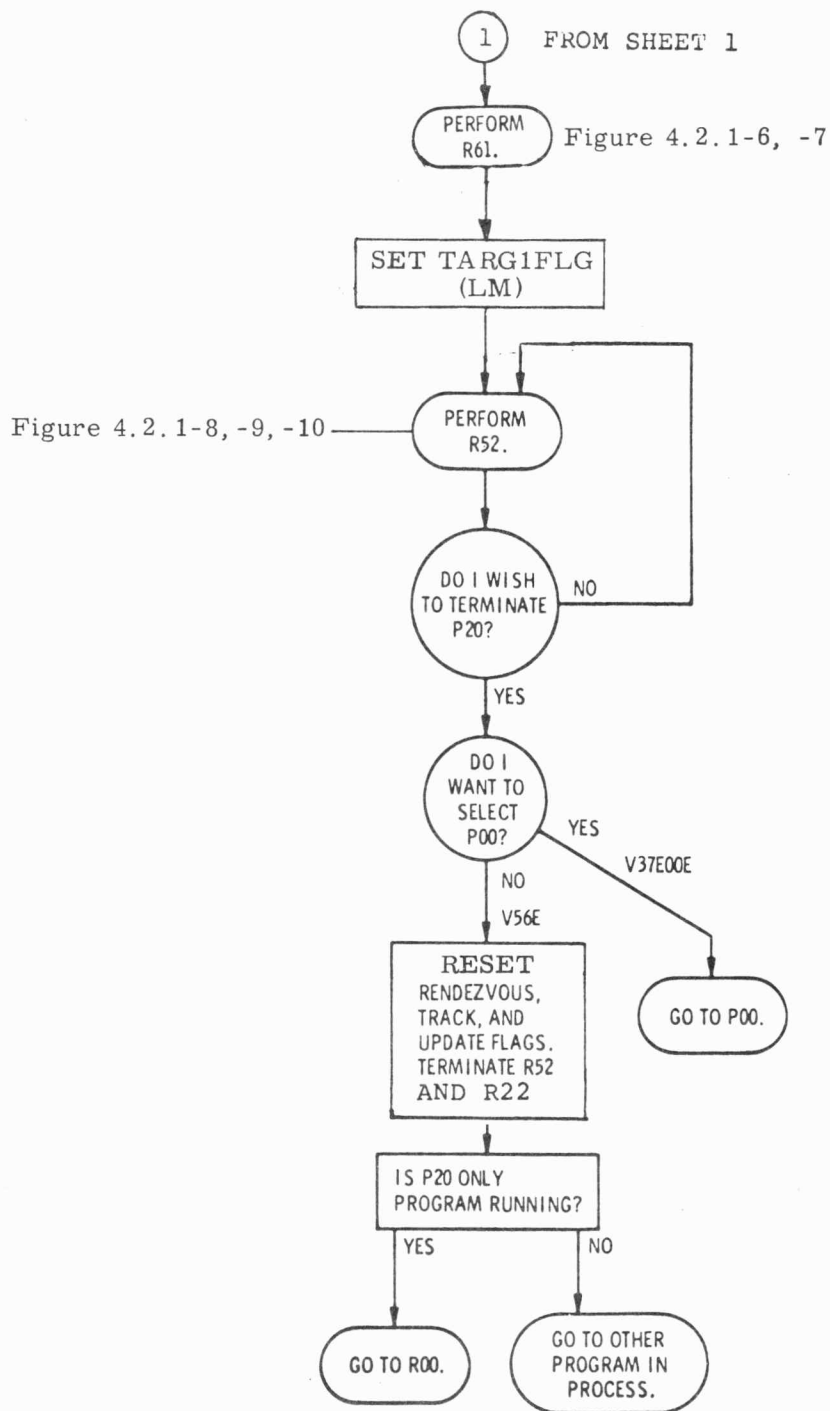
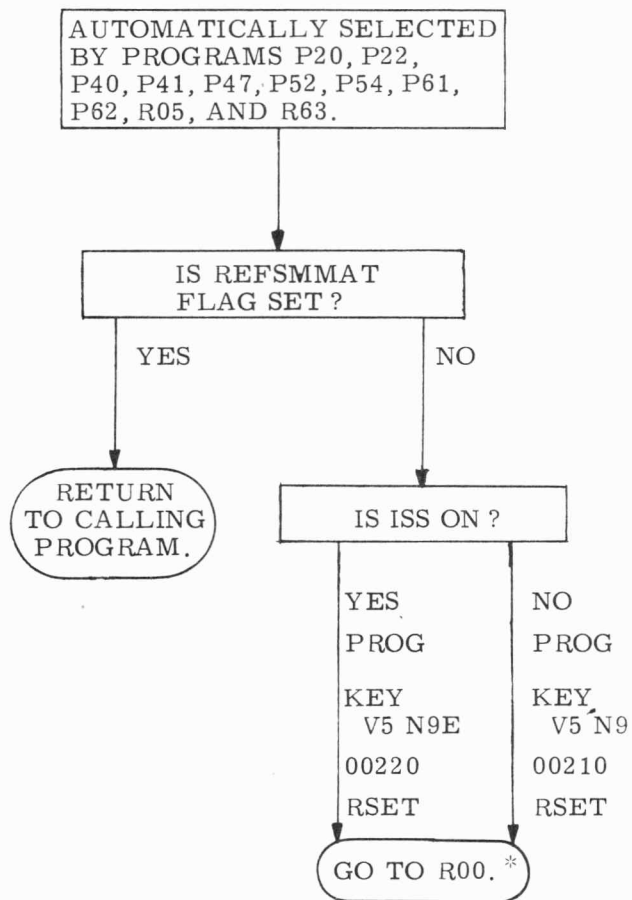


Figure 4.2.1-3 Rendezvous Navigation Program (P20) (Sheet 2 of 2)



* IN R00 TURN ON IMU AND
SELECT PROGRAM TO RE-
ALIGN IMU (P51 OR P53);
UPON COMPLETION RE-
SELECT DESIRED PROGRAM.

Figure 4.2.1-4. IMU Status Check Routine (R02)

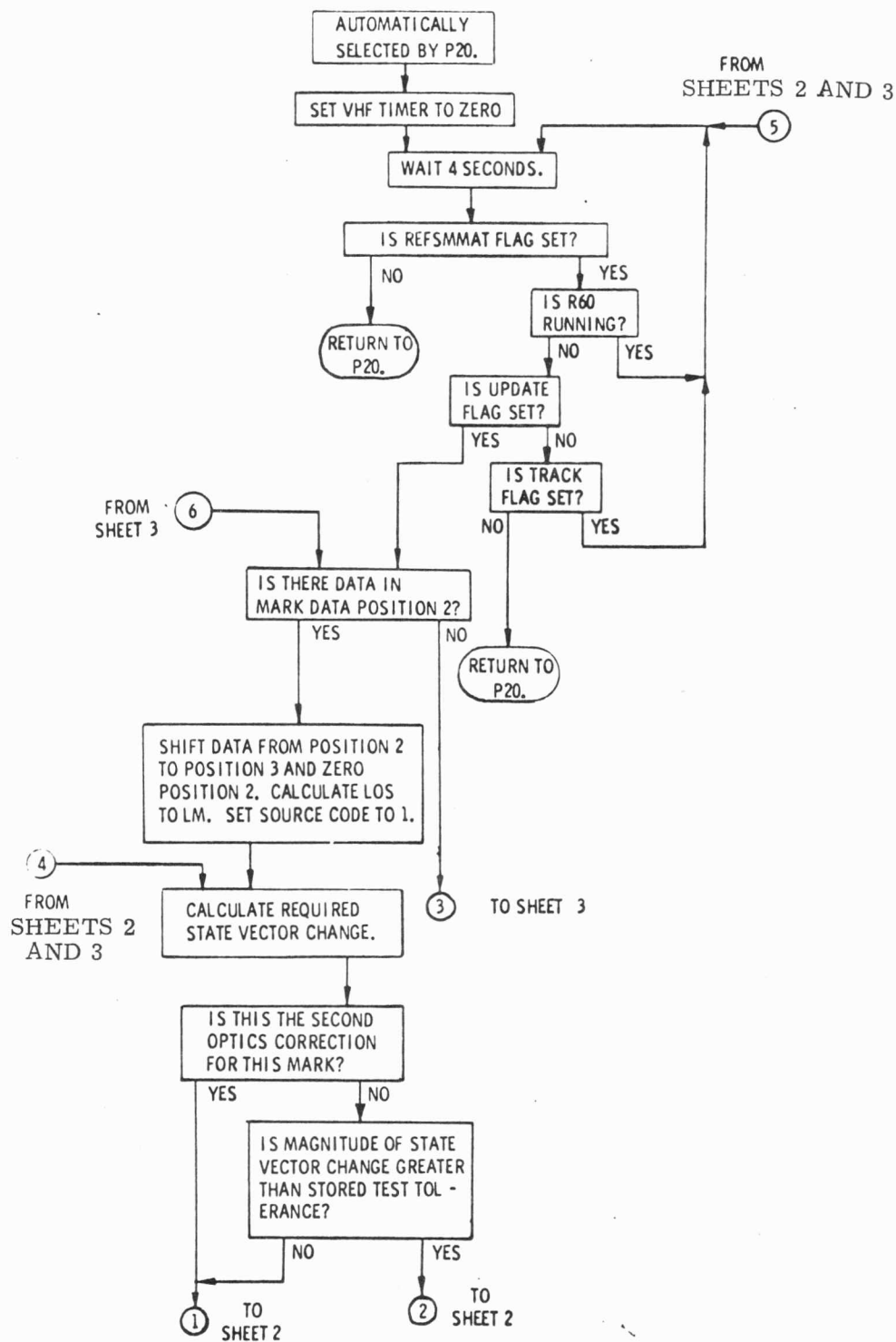


Figure 4. 2. 1-5, Rendezvous Tracking Data Processing Routine (R22) (Sheet 1 of 3)

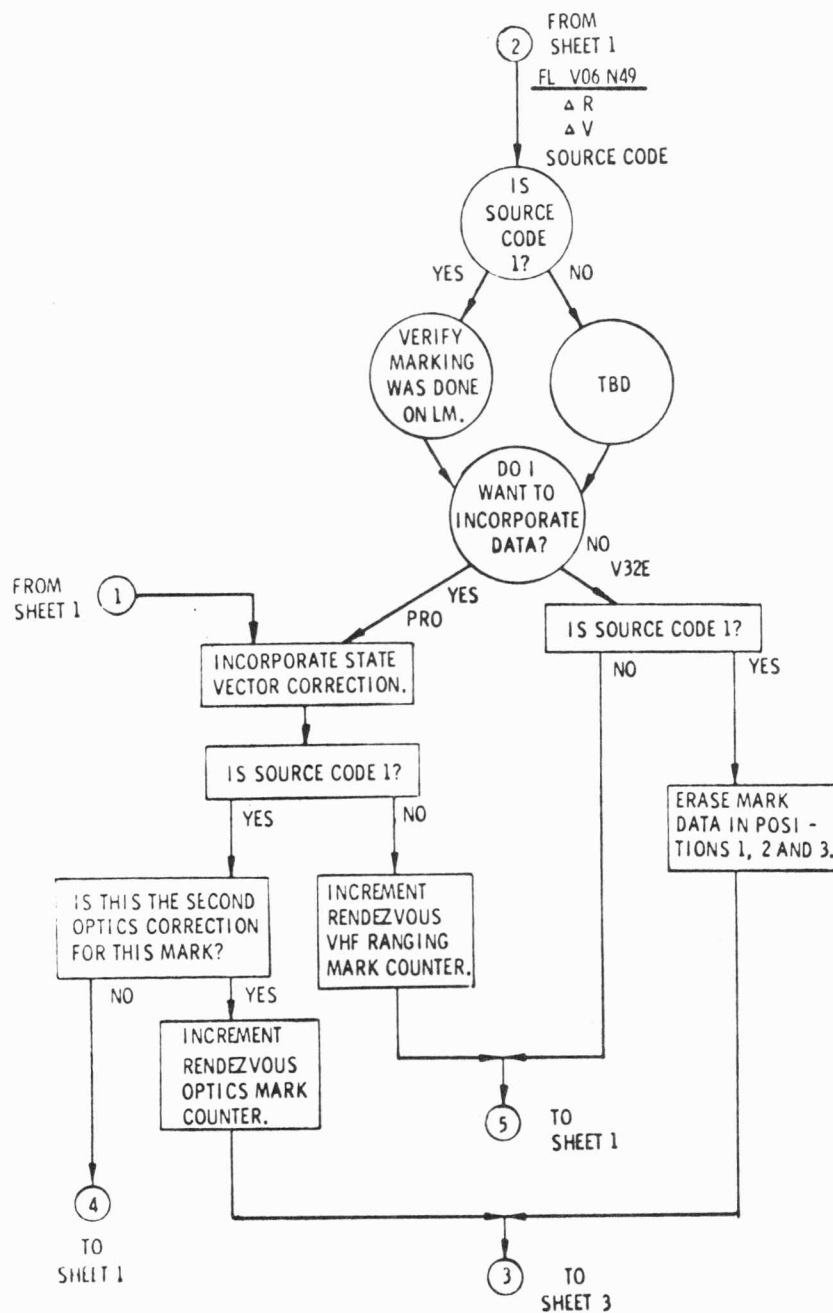


Figure 4. 2. 1-5. Rendezvous Tracking Data Processing Routine (R22) (Sheet 2 of 3)

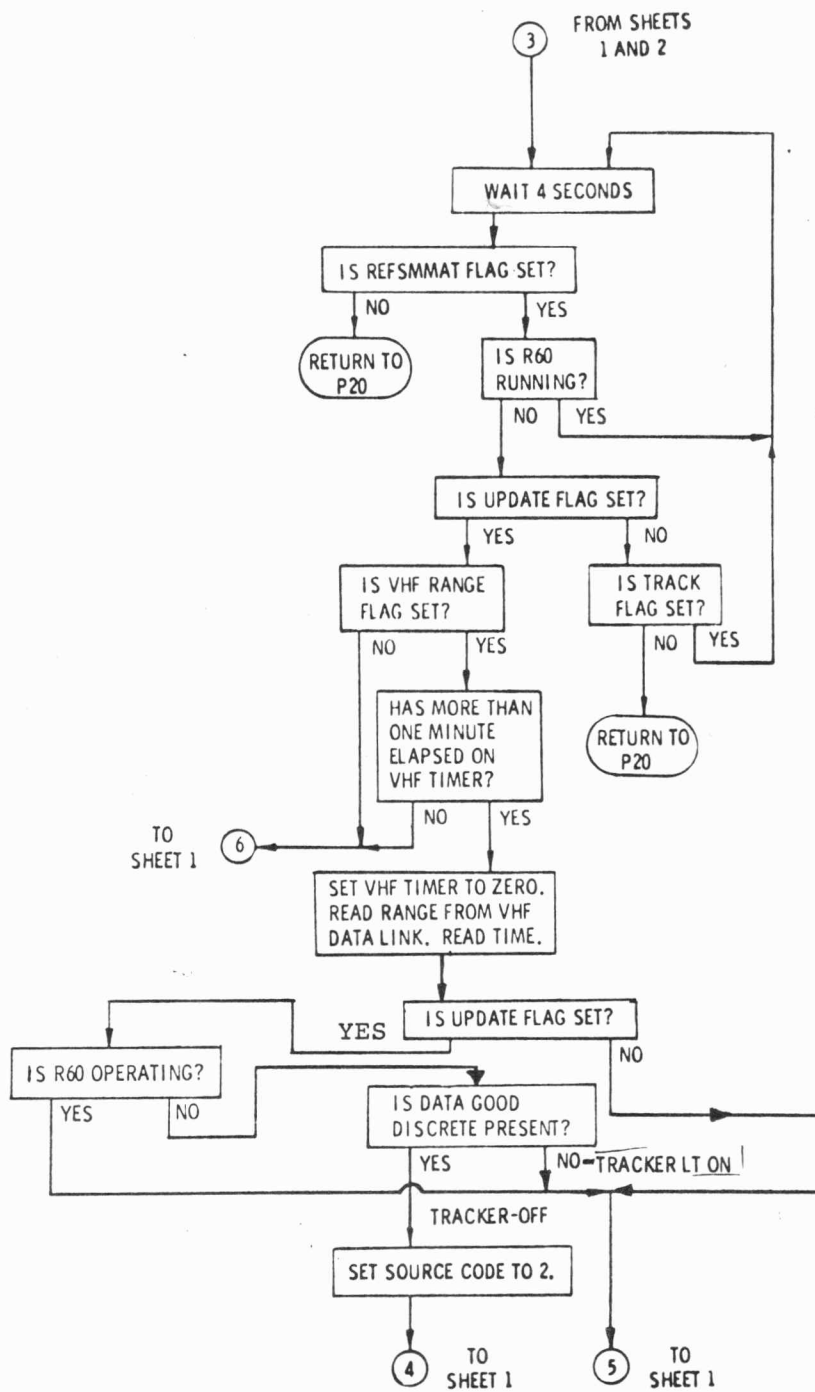


Figure 4. 2. 1-5, Rendezvous Tracking Data Processing Routine (R22) (Sheet 3 of 3)

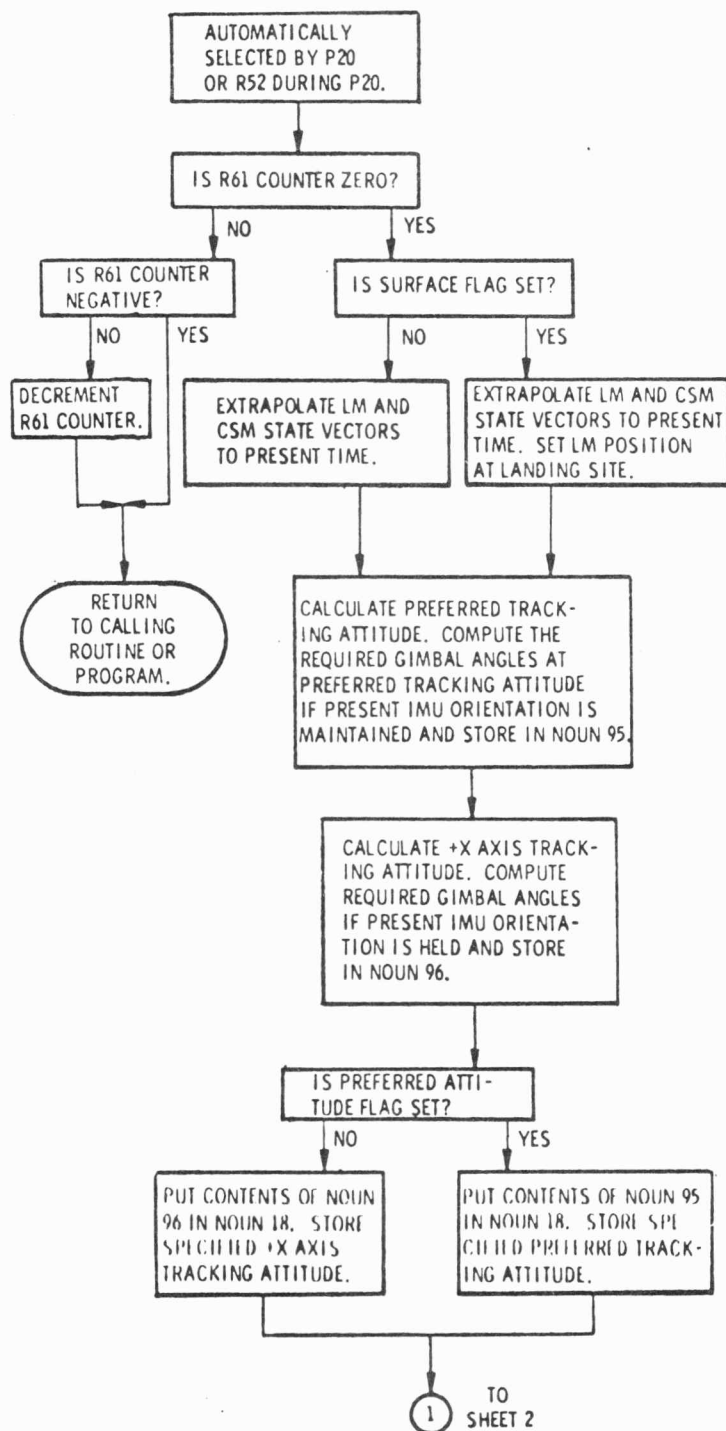


Figure 4.2.1-6. Tracking Attitude Routine (R61) (Sheet 1 of 2)

From Sheet 1

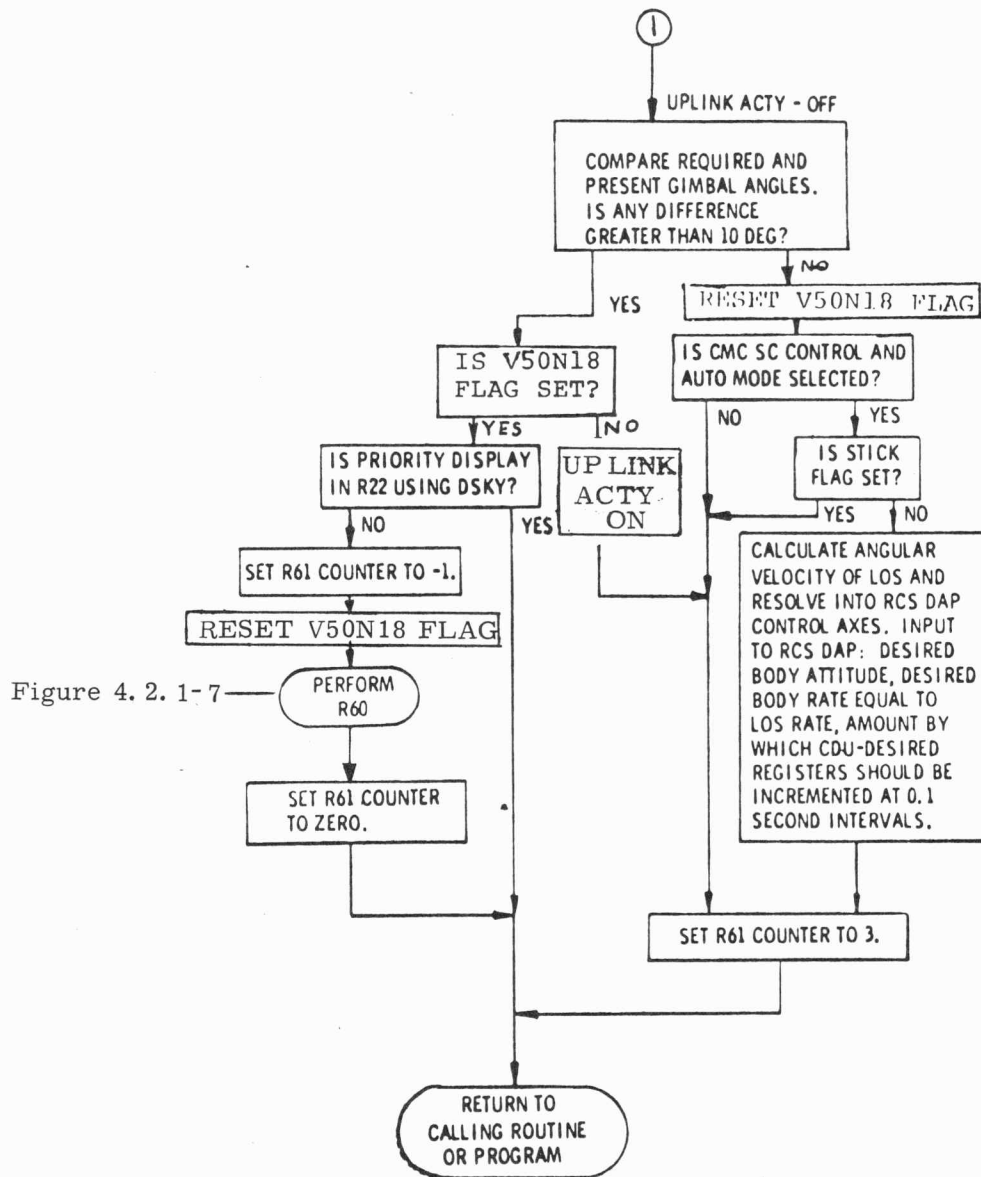


Figure 4.2.1-6. Tracking Attitude Routine (R61) (Sheet 2 of 2)

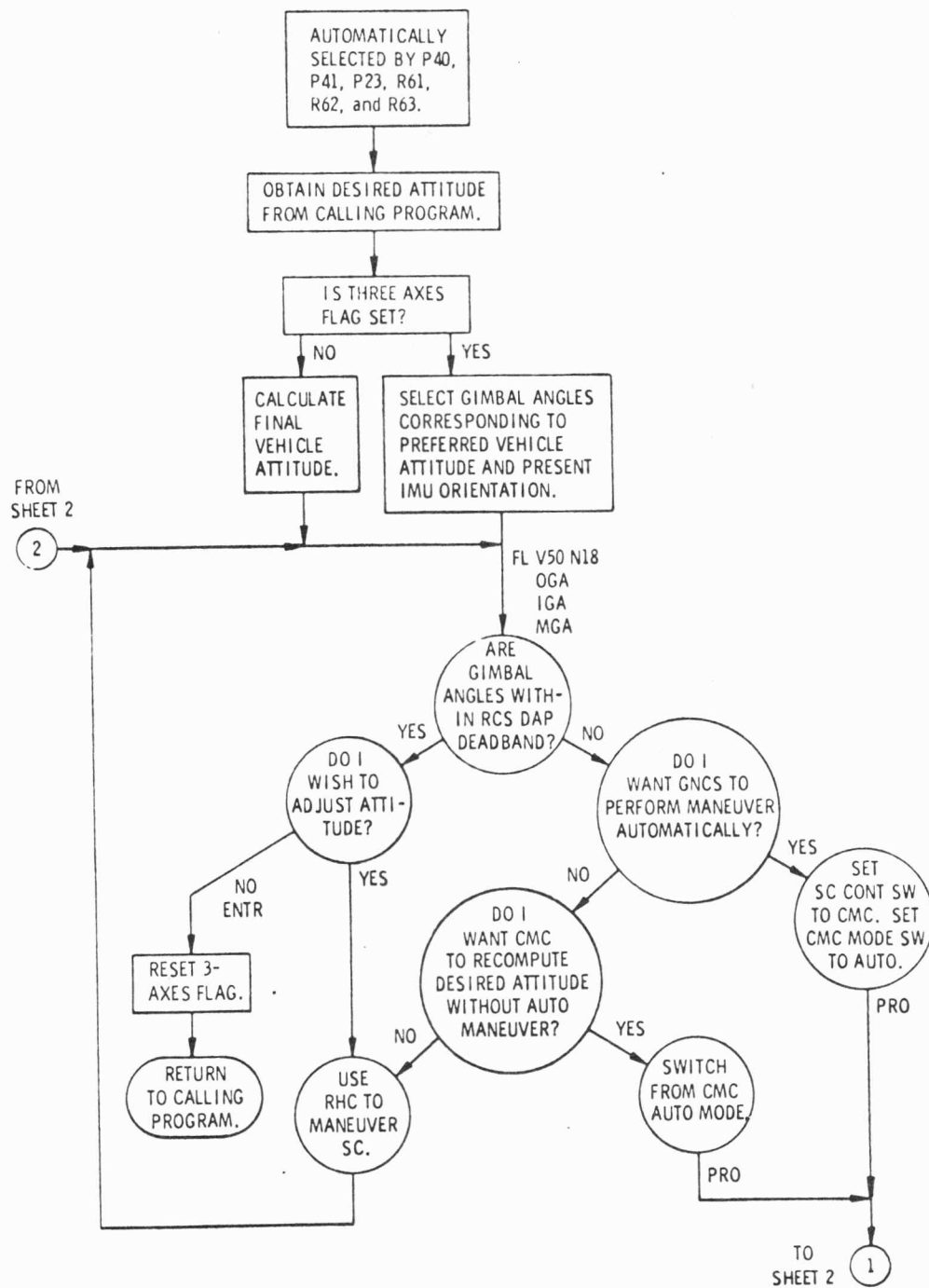


Figure 4. 2. 1-7. Attitude Maneuver Routine (R60) (Sheet 1 of 2)

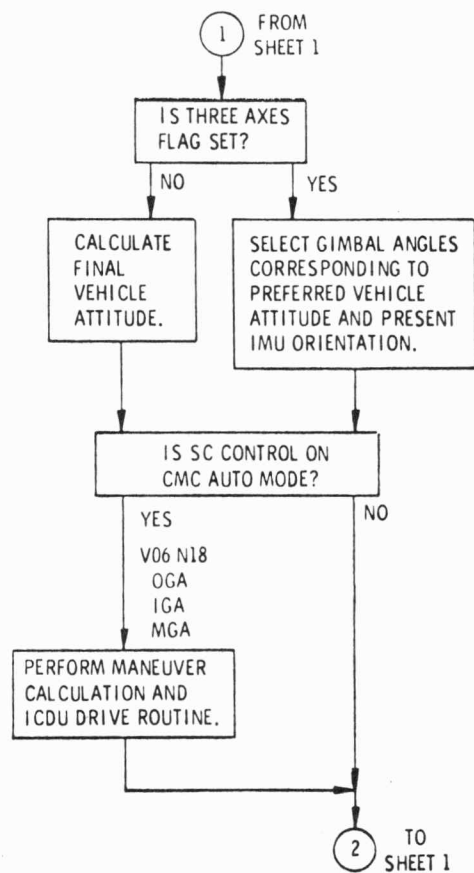


Figure 4. 2. 1-7, Attitude Maneuver Routine (R60) (Sheet 2 of 2)

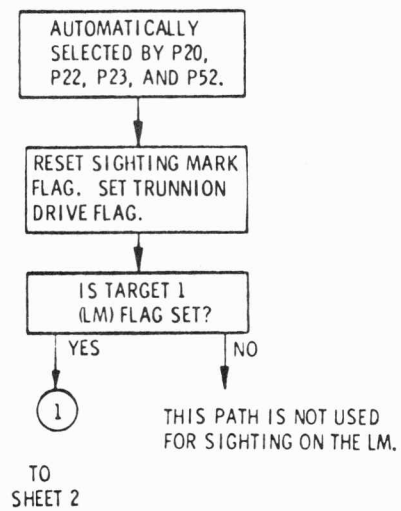


Figure 4. 2.1- 8. Automatic Optics Positioning Routine (R52) (Rendezvous)
(Sheet 1 of 2)

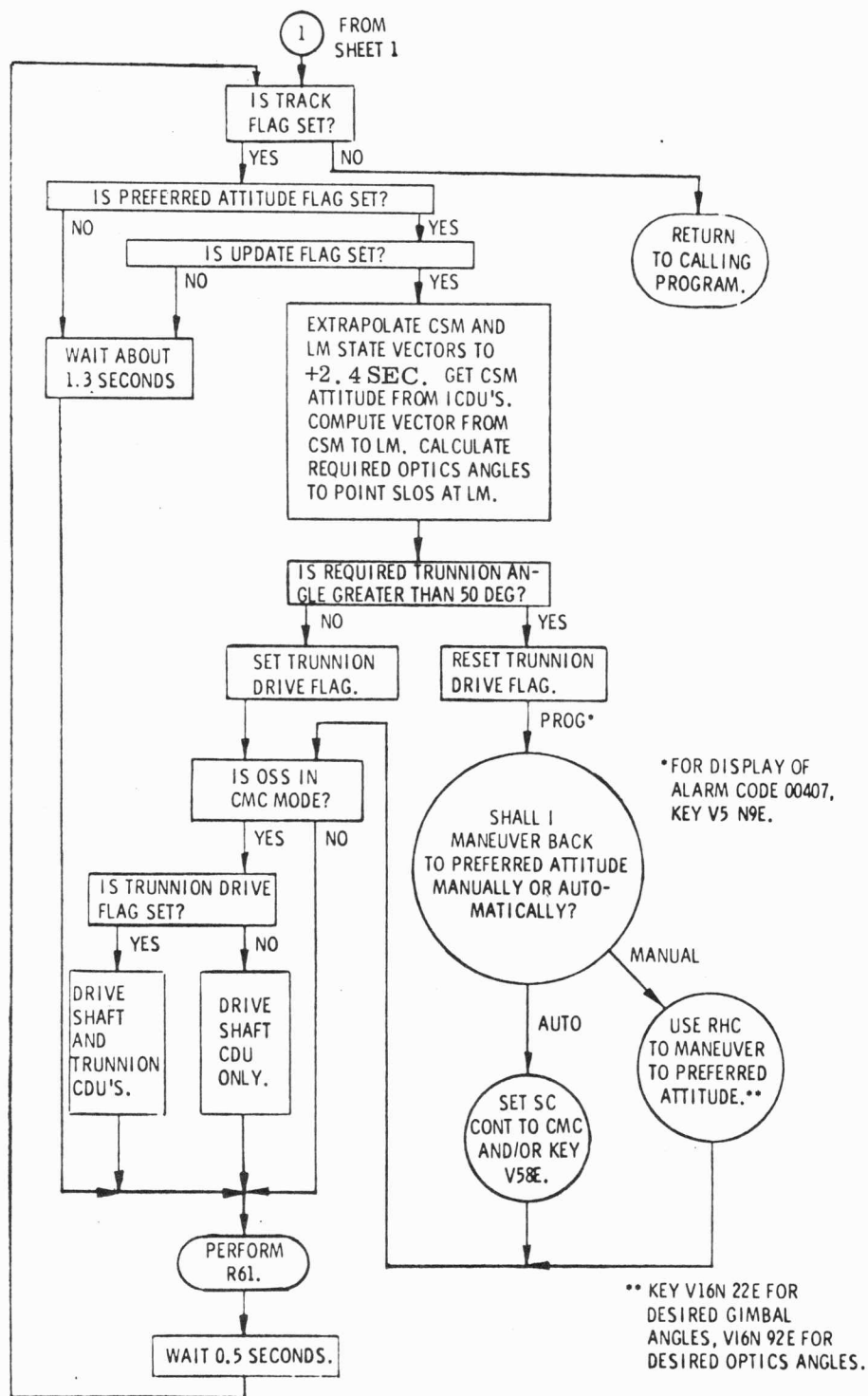


Figure 4. 2. 1-8. Automatic Optics Positioning Routine (R52) (Rendezvous)
(Sheet 2 of 2)

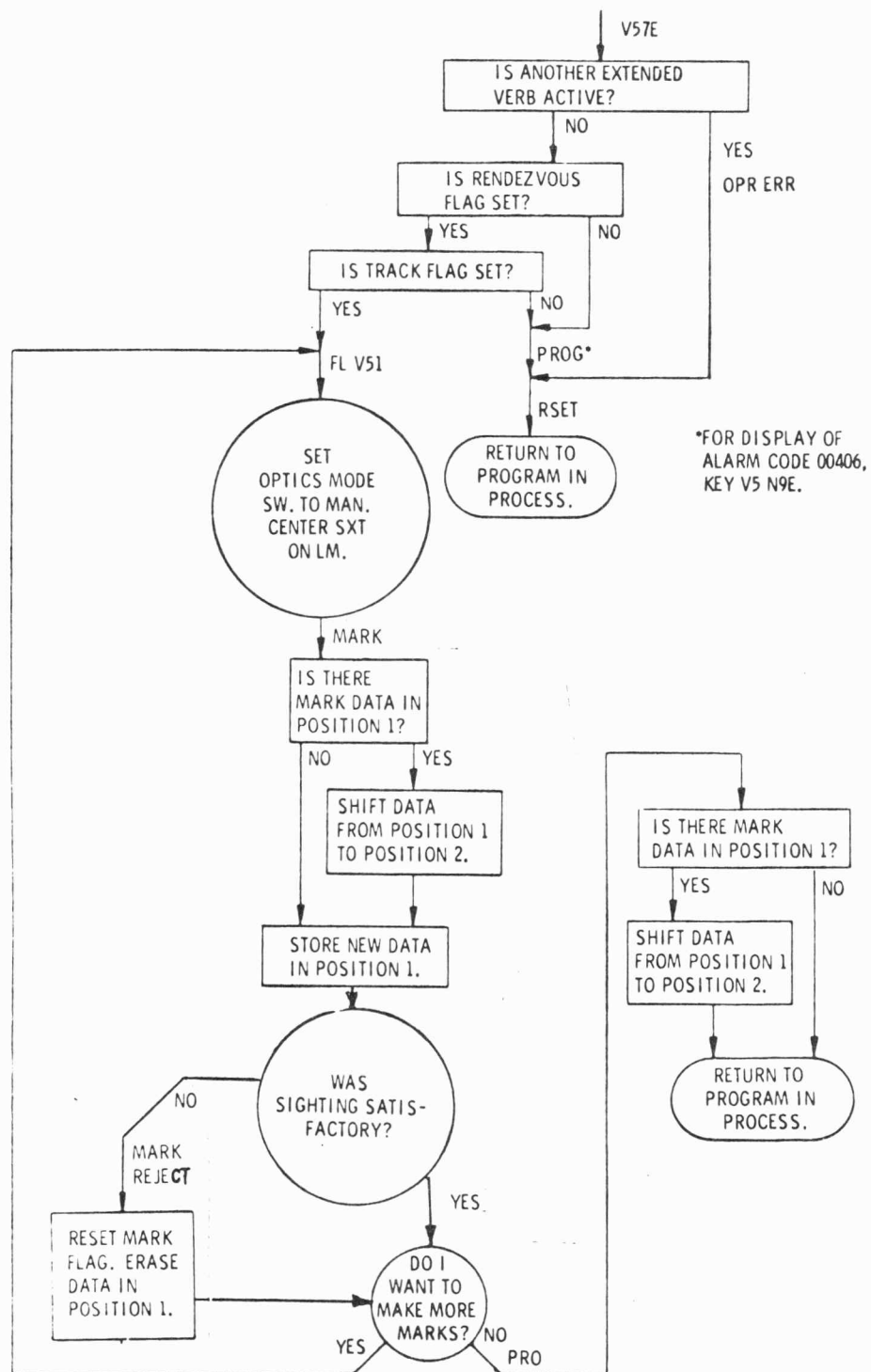


Figure 4. 2. 1-9. Rendezvous Tracking Sighting Mark Routine (R21)

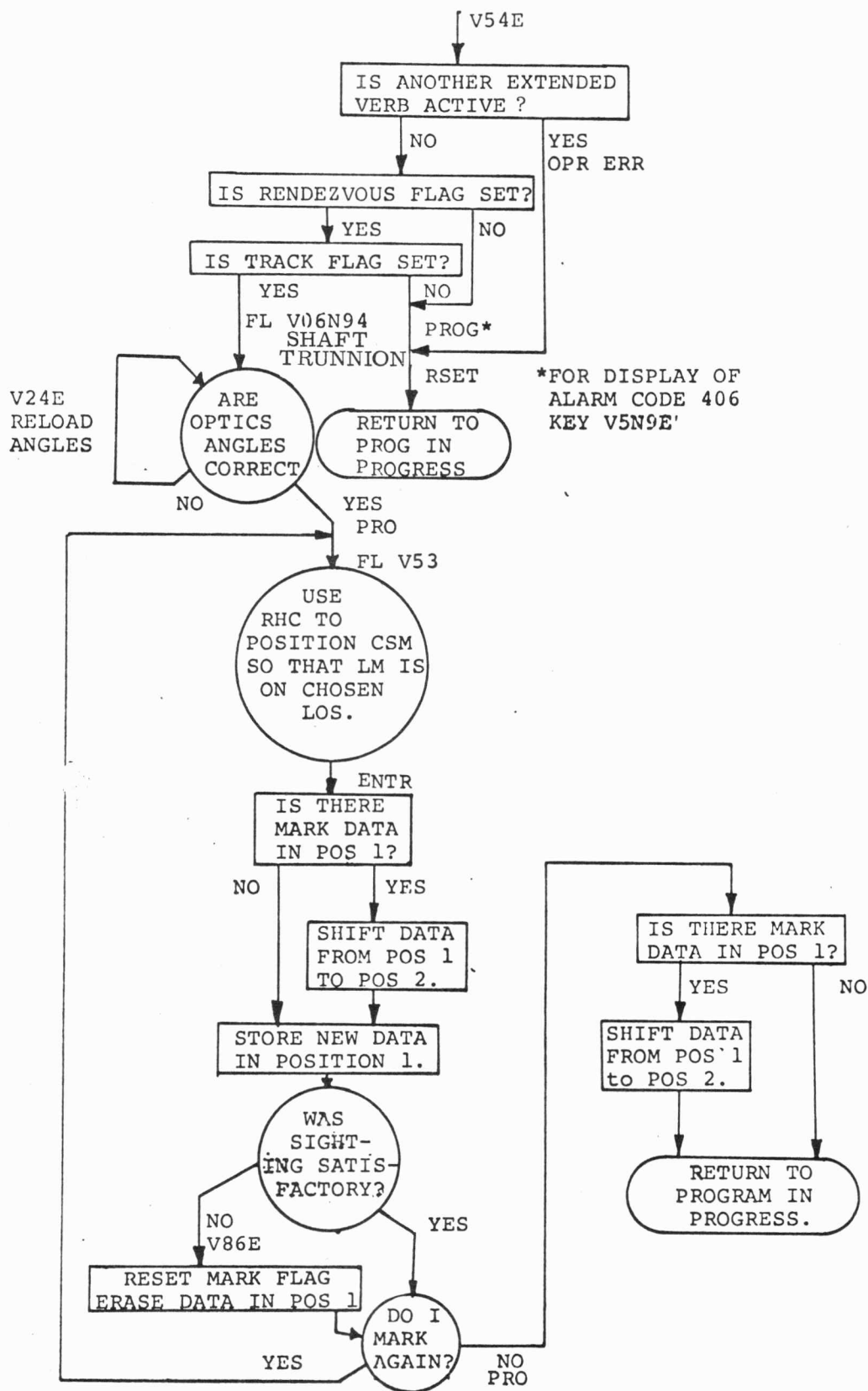


Figure 4.2.1-10. Backup Rendezvous Tracking Sighting Mark Routine (R23)

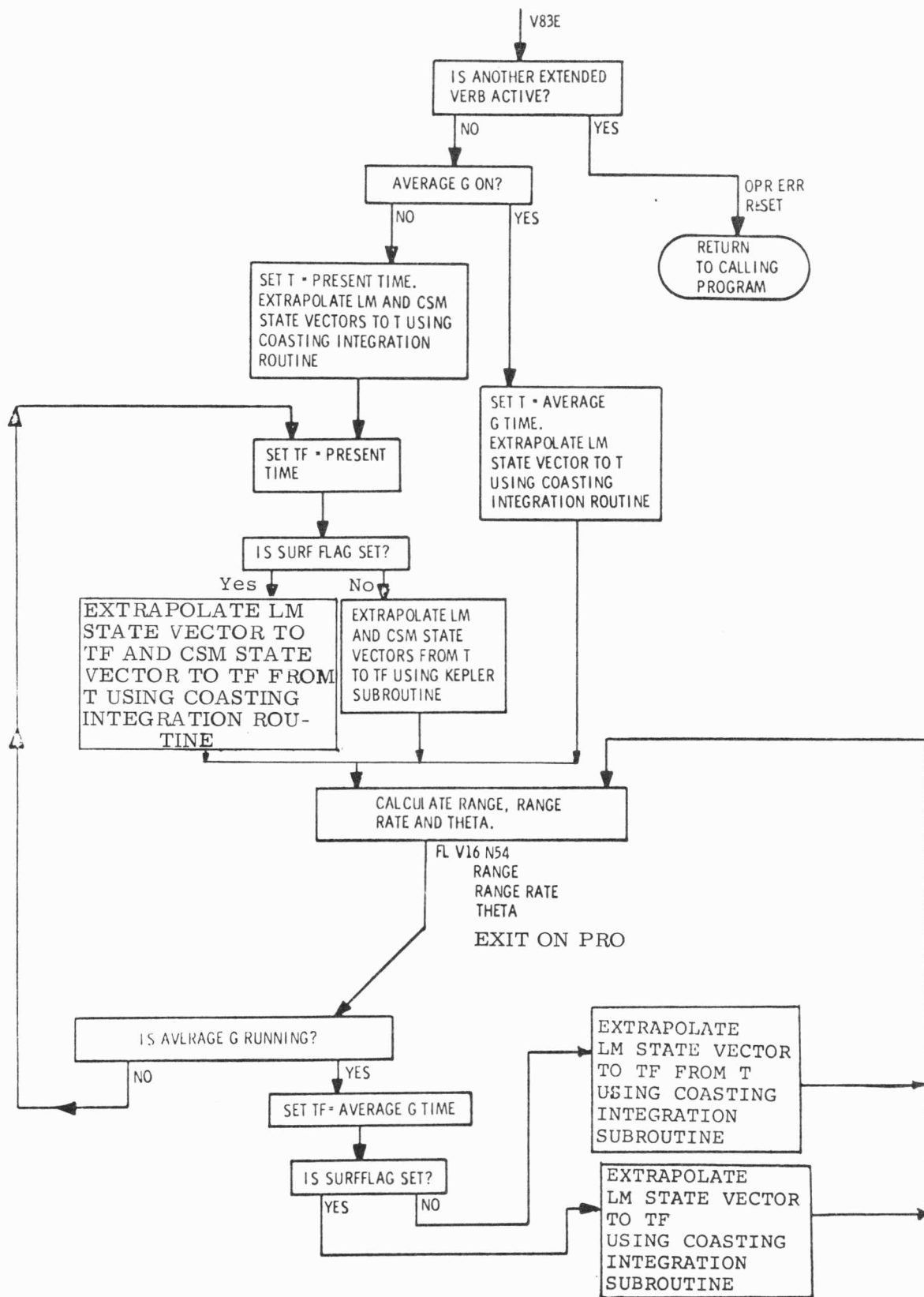


Figure 4. 2. 1-11. Rendezvous Parameter Display Routine No. 1 (R31)

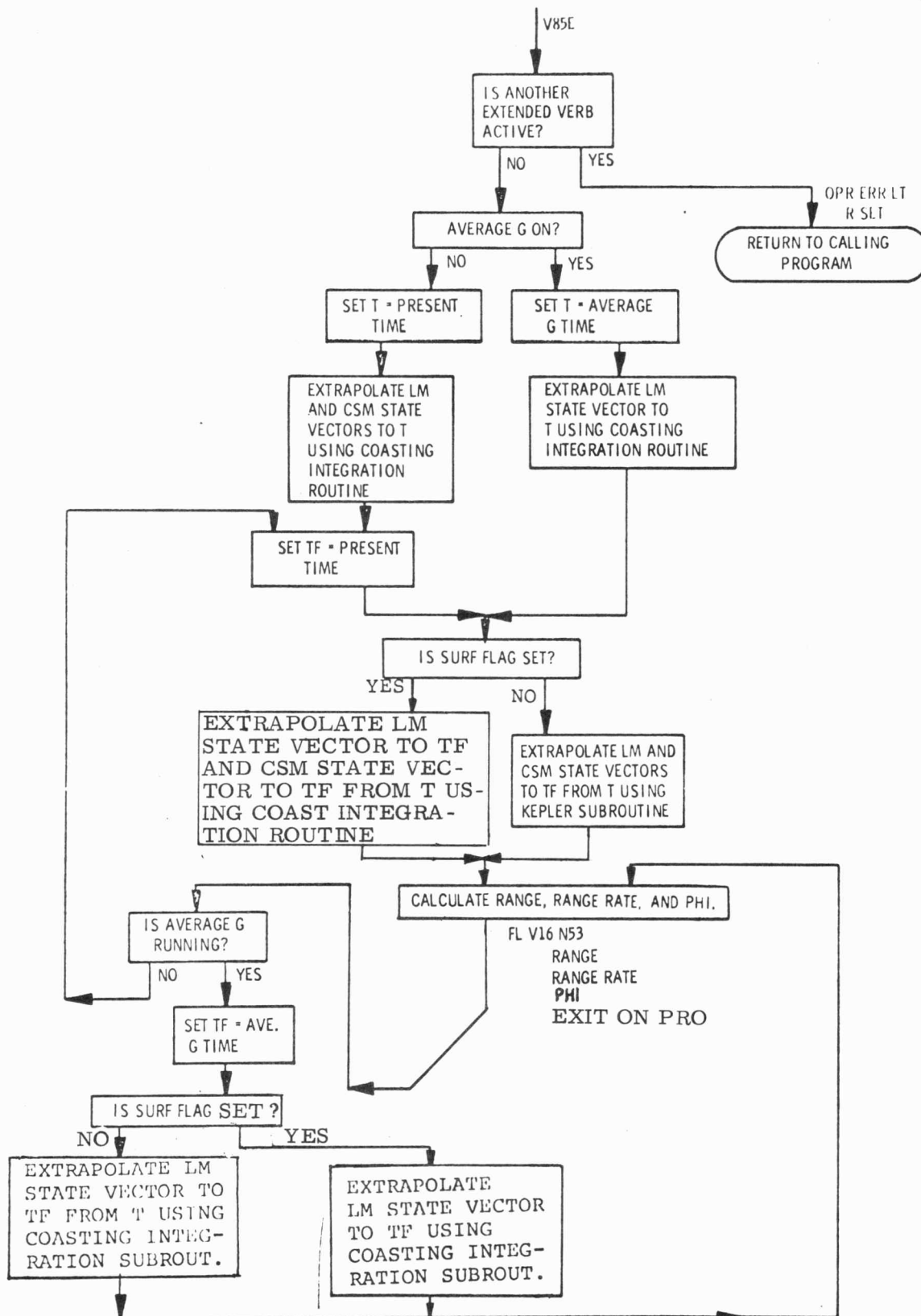


Figure 4.2.1-12. Rendezvous Parameter Display Routine No. 2 (R34)

If, on the first pass through R61 after P20 entry (V50N18 flag set), any required gimbal-angle change is greater than 10 deg, R61 calls the Attitude Maneuver Routine (R60). If, on subsequent passes through R61 (V50N18 flag reset), any required gimbal-angle change is greater than 10 deg, R61 turns on the UPLINK ACTY light but does not call R60. Should the astronaut wish an R60 maneuver performed, he would key VERB 58 ENTR, setting the V50N18 flag (and resetting the STICK flag) and instructing R61 to call R60.

After commanding the maneuver or providing the appropriate RCS DAP input, R61 returns to the calling program.

R60— The Attitude Maneuver Routine (Figure 4.2.1-7) maneuvers the spacecraft to an attitude specified by the calling program. The astronaut can choose to perform the maneuver manually or automatically. If manually, the maneuver is performed with the rotational hand controller (RHC) while the astronaut monitors the FDAI; if automatically, the maneuver is performed by CMC-commanded RCS jet firings.

R52— During rendezvous navigation, the Automatic Optics Positioning Routine (Figure 4.2.1-8) keeps the CSM optics pointed at the LM. Calculating the LOS to the LM, with R61 maintaining tracking attitude, R52 drives the optics shaft and trunnion accordingly until the TRACK flag is reset.

R21— The Rendezvous Tracking Sighting Mark Routine (Figure 4.2.1-9) is called by the crew's keying VERB 57 ENTR during R22. A flashing VERB 51 requests the astronaut to center SXT on LM and to mark. R21 is terminated by the crew's depressing the PRO key.

R23— The Backup Rendezvous Tracking Sighting Mark Routine (Figure 4.2.1-10) is similar to R21 except that R23 uses the crew optical alignment sight (COAS) rather than the sextant (SXT). R23 is called by the crew's keying VERB 54 ENTR and is terminated by PRO.

R31/

R34— The Rendezvous Parameter Display Routines (Figures 4.2.1-11 and -12) display range and range rate (between the CSM and LM) calculated from the stored LM and CSM state vectors. In addition, R31 displays the

current angle (θ) between the CSM plus X-axis and the local-horizontal plane. R34 displays the current angle (ϕ) between the SXT SLOS and the local-horizontal plane.

Before entering P20, the crew must perform the DAP Data Load Routine (R03).

Upon the crew's selection of P20 (VERB 37 ENTR 20 ENTR), the program performs the IMU Status Check Routine (R02, Figure 4.2.1-4) and illuminates the PROG alarm lamp should the ISS be off or the IMU orientation be unknown. Should the PROG lamp illuminate, the crew must key VERB 05 NOUN 09 ENTR in order to read the alarm code (00210, ISS not on; 00220, IMU orientation unknown). A flashing VERB 37 indicates that, as a result of the alarm, the program has entered the Final Automatic Request Terminate Routine (R00).

Next, the program automatically selects the preferred tracking-attitude option and LM state-vector option. The crew can change either of these by the following DSKY entries:

VERB 76 ENTR selects preferred tracking attitude.
VERB 77 ENTR selects plus X-axis track attitude.
VERB 80 ENTR selects LM state-vector update.
VERB 81 ENTR selects CSM state-vector update.

P20 next sets the following flags:

V50N18 Flag — enables R60 and the display of required
gimbal angles for a maneuver
to the desired tracking attitude.

TRACK Flag — enables automatic maneuver, optics
pointing, and state-vector update.

UPDATE Flag — enables state-vector update.

RENDEZVOUS

Flag — enables total P20 operation.

The rendezvous-optics and VHF-ranging mark counters are next set to zero, and the CSM and LM state vectors are extrapolated to the present time. P20 then calls the Rendezvous Tracking Data Processing Routine (R22, Figure 4.2.1-5), which will

continue to operate while P20 is active. The program then calls the Tracking Attitude Routine (R61, Figure 4.2.1-6), which uses VECPOINT to compute the CSM tracking attitude required for pointing the optics and radar transponder at the LM. VECPOINT is, basically, a method of taking the cross product of the present and desired LOS and computing the rotation angle required to align the two about the resulting cross-product vector. (See subsection 3.6 of the current CSM GSOP.) If attaining the preferred tracking attitude requires a gimbal-angle change of less than 10 deg, R61 will issue the command signals to the RCS DAP (SC CONT switch in CMC; CMC MODE switch in AUTO; STICK flag reset). If attaining the preferred tracking attitude requires a maneuver of 10 deg or larger, R61 calls the Attitude Maneuver Routine (R60, Figure 4.2.1-7). (NOTE: During P20 operation, R61 is called every 2 sec; only on every fourth pass, however, is R61 allowed to complete its cycle. After an initial pass has established a tracking attitude of less than 10 deg, R61 resets the V50N18 flag, disabling R60 on subsequent passes. Therefore, should, on a subsequent pass through R61, any required gimbal-angle change be found greater than 10 deg, R61 would illuminate the UPLINK ACTY light, and R60 would only be allowed to perform the required maneuver upon the astronaut's setting the V50N18 flag by keying VERB 58 ENTR.)

Entering R60, the program flashes VERB 50 NOUN 18 and displays the desired gimbal angles in 1/100 degree:

R1-OG, roll
R2-IG, pitch
R3-MG, yaw

Should the astronaut desire the maneuver to be performed by the autopilot, he would place the SC CONT switch in CMC, the CMC MODE switch in AUTO, and would then depress the PRO key on the DSKY, signaling the RCS DAP to begin the maneuver. (It is also assumed that VERB 46 ENTR has been keyed and that the RCS DAP is operating.)

During the maneuver, a non-flashing VERB 06 NOUN 18 displays the final gimbal angles, and the astronaut monitors the maneuver on the FDAI ball and needles. Should the maneuver approach gimbal lock, the astronaut would take over manually and complete the maneuver using the rotation hand controller (RHC).

At the completion of the maneuver—or its premature termination by the astronauts' use of the RHC—R60 recycles, and VERB 50 NOUN 18 again flashes the desired gimbal angles. If the displayed angles are within RCS deadband limits and no rotation

about the pointing vector—to obtain wings level—is desired, the astronaut would key ENTR, and R60 would exit. If further attitude adjustment were required, however, the astronaut would perform the adjustment with the RHC while referencing the FDAI needles and ball. Keying ENTR terminates R60 and allows R61 to continue computing and maintaining the pointing vector along the LM LOS as long as the SC CONT switch is in CMC AUTO.

The program next enters the Automatic Optics Positioning Routine (R52). R52 extrapolates the CSM and LM state vectors to the present plus 2.4 seconds, gets the CSM attitude from the ICDUs, computes the vector from the CSM to LM, and calculates the required optics angles to point the sextant line of sight at the LM. If the resulting trunnion is greater than 50 deg, the PROG alarm illuminates. (For display of alarm code 00407, the astronaut must key in VERB 05 NOUN 09 ENTR.) Keying VERB 58 ENTR sets the V50N18 Flag, allowing R60 to be called to maneuver the spacecraft back to the preferred attitude.

If the required trunnion is less than 50 deg, R52 drives the shaft and trunnion CDUs to align the optics with the LM. The program then recycles through R61, and both routines (R61 and R52) continue to operate in approximately 2-second cycles.

When the astronaut wishes to take SXT marks on the LM, he keys VERB 57 ENTR, which calls the Rendezvous Tracking Sighting Mark Routine (R21, Figure 4.2.1-9). As described earlier, R61 will automatically maintain the preferred tracking attitude. If desired, placing the CMC MODE switch in FREE allows the astronaut to use the minimum impulse controller (MIC) to hold the LM in the field of view.

Once entered, R21 flashes VERB 51 on the DSKY, requesting the astronaut to "please mark." The astronaut then selects the manual optics mode, centers the LM in the reticle, and depresses the mark button. If the mark was satisfactory, the astronaut waits the prescribed time (based on geometry, timeline, etc.), recenters the LM in the reticle, and repeats the mark (if more marks are desired). If the mark was not satisfactory, the astronaut depresses the reject button and repeats the mark procedure. When sufficient marks have been taken, the astronaut keys in PRO to terminate R21. If any mark results in an excessive update, a priority display (flashing VERB 06 NOUN 49) will automatically interrupt any program-initiated display and present the magnitude of the excessive update:

Flashing VERB 06 NOUN 49 — R1, ΔR (0.1 n. mi.); R2, Δv (0.1 ft/sec); R3,
Source Code (00001, optics; 00002, VHF
ranging).

Depressing the PRO key incorporates the update data; keying VERB 32 ENTR rejects the data. When rendezvous has been completed, the crew can exit P20 either by keying VERB 37 ENTR 00 ENTR, which discontinues all programs in progress, or by keying VERB 56 ENTR, which discontinues P20 and calls the other program in progress.

For the plus X-axis tracking-attitude option, using the backup optics (COAS), the crew keys VERB 77 ENTR immediately after entering P20 and keys VERB 54 ENTR (rather than VERB 57 ENTR) after the attitude maneuver has been completed. VERB 54 calls the Backup Rendezvous Tracking Sighting Mark Routine (R23). The DSKY then flashes VERB 06 NOUN 94 and presents in registers 1 and 2 the equivalent shaft angle (SA) and equivalent trunnion angle (TA) for the alternate LOS in the NAVBASE Coordinate System. If the astronaut elects to use the COAS, the nominal values for these angles are 00000 in R1 and 57470 in R2. If the angles displayed are not correct for the selected LOS, the astronaut keys VERB 24 ENTR and loads the correct values. When the correct angles are displayed, the astronaut keys in PRO and will get a flashing VERB 53, "please perform alternate LOS sighting mark." The astronaut will then use the RHC to align precisely the LM along the alternate LOS. He then depresses the ENTR key on the DSKY. When sufficient marks have been made, the astronaut depresses the PRO key. To reject a mark, the astronaut keys VERB 86 ENTR and repeats the mark procedure. Again, when rendezvous has been completed, VERB 37 ENTR 00 ENTR terminates all programs running; VERB 56 ENTR terminates only P20.

Although we have not mentioned how VHF range data are initiated, the crew procedure is simply to key VERB 87 ENTR whenever range data are desired; VHF range taking will then be continued automatically until terminated by the crew's selection of VERB 88 ENTR or by the execution of any program change, that is, any VERB 37.

4.2.1.3 Program Alarms

Four PROG alarm possibilities are associated with P20:

- 00210—ISS not on
- 00220—IMU orientation not known
- 00407—trunnion angle greater than 50 deg
- 00406—P20 not in progress

The first two alarms (00210 and 00220) would occur immediately after P20 is entered and the program calls the IMU Status Check Routine (R02). Viewing a PROG alarm

on the DSKY, the crew would key VERB 05 NOUN 09 ENTR to identify the abnormality, depress KEY REL and RSET when the alarm is identified, and respond to flashing VERB 37 by entering the appropriate program for correcting the abnormality (P51).

The third alarm (00407) would occur during R52. After verifying the alarm, by keying VERB 05 NOUN 09 ENTR, the crew would either manually maneuver the vehicle back to the preferred tracking attitude or key VERB 58 ENTR (CMC MODE in AUTO) and allow the RCS DAP to perform the required maneuver. Should the astronaut elect to perform the maneuver manually, he would obtain a display of the desired gimbal angles by keying VERB 16 NOUN 22 ENTR and use the RHC to maneuver the vehicle. (Desired optics angles are displayed by keying VERB 16 NOUN 92 ENTR.) Alarm 00407 is also likely to be displayed, irrelevantly, following selection of P20 after a thrusting maneuver (P40/41) having a thrust vector greater than 50 deg from the optics shaft axis. No crew action is required; PROG will remain illuminated until R60 has been completed.

Alarm Code 00406 would occur if the Rendezvous Tracking Sighting Mark Routine (R21) or the backup mark routine (R23) were called and P20 were not running. Verified by VERB 05 NOUN 09 ENTR, the alarm is cleared by VERB 37 ENTR 20 ENTR.

4.2.1.4 Restrictions and Limitations

The Rendezvous Navigation Program (P20) can only solve for the relative position and velocity of one orbiting vehicle with respect to another. The extent to which the state vector updated by P20 conforms to actual position and velocity in inertial space will depend, therefore, upon how well the inertial position and velocity of the vehicle whose state vector is not updated are known. Since the primary concern in rendezvous navigation, however, is relative position and velocity, the limitations regarding inertial state-vector accuracy are of concern only as a factor to be considered in determining the relative state of the two vehicles. If there were no uncertainties in the direct measuring of range and LOS between the two vehicles, determining the relative state vector would be simply a matter of taking measurements, comparing the results with values predicted on the basis of the current best estimate of the two state vectors, and updating one of the estimated states such that the predicted and measured values agree. Measuring uncertainties do exist, however, calling for a statistical weighting matrix (W-matrix) and an a priori sensor variance for determining how much emphasis is to be given to the measured data, in updating the state, and how much is to be given to the current estimate. Initially, the W-matrix is based on statistical studies to determine what the expected

mean-square errors in position and velocity will be before any measurements are taken; as measurements are taken, however, and the confidence in the relative state vector increases, the W-matrix is itself updated such that statistical weighting becomes more and more in favor of the current estimate and less in favor of new measurements. In time, obviously, the weighting in favor of the measurements becomes so small as to render them insignificant. To prevent this, the W-matrix must be periodically re-initialized to its padloaded, or reloaded, values. It is desirable, therefore, to schedule measurements such as to use a W-matrix that has had 15 or 20 minutes of marking when updating the state vector for a thrusting maneuver. (See typical time line, Figure 4.2.1-13.)

Another factor regarding measurements is the minimum time between sighting marks. When the CMC accepts a mark, three ICDUs, two OCDUs, and the time of the mark are stored in a buffer (position 1). When a second mark is taken, the data in position 1 are transferred to position 2, and the new data are stored in position 1. Should marks be taken faster than about one every 20 seconds, there is a chance that the data in position 2 will be lost. Also, there is a chance that one of the last two marks will be lost unless about 15 seconds are allowed before proceeding (PRO) after the last mark.

An additional restriction regarding the W-matrix is that it should never be re-initialized to values greater than 328 ft/sec and 51,647 ft.

A limiting factor regarding VHF range data is that beyond 327.67 n. mi. the input counter to the CMC is saturated and VHF range data cannot be used. Also, depending upon scaling, there is a minimum range at which P20 is effective. Although it is difficult to establish definite limits, since scaling may differ for different missions (e.g., earth versus lunar), operation with current scaling is not recommended for ranges less than about 3 n. mi.

4.2.1.5 Program Coordination and Procedures

The Rendezvous Navigation Program (P20) can operate either alone or in conjunction with any of the programs listed in the bottom-right-hand box of Figure 4.2.1-2. P20 is entered by keying VERB 37 ENTR 20 ENTR on the DSKY. Subsequent selection of any one of the other programs listed in Figure 4.2.1-2 changes the DSKY program number but allows P20 to continue operating in the background. Accordingly, the crew can, upon a flashing display during one of the named programs, call either the Rendezvous Tracking Sighting Mark Routine (R21-VERB 57 ENTR) or the Backup Rendezvous Tracking Sighting Mark Routine (R23-VERB 54 ENTR), take the

CSM MONITOR OF NOMINAL LM ACTIVE RENDEZVOUS

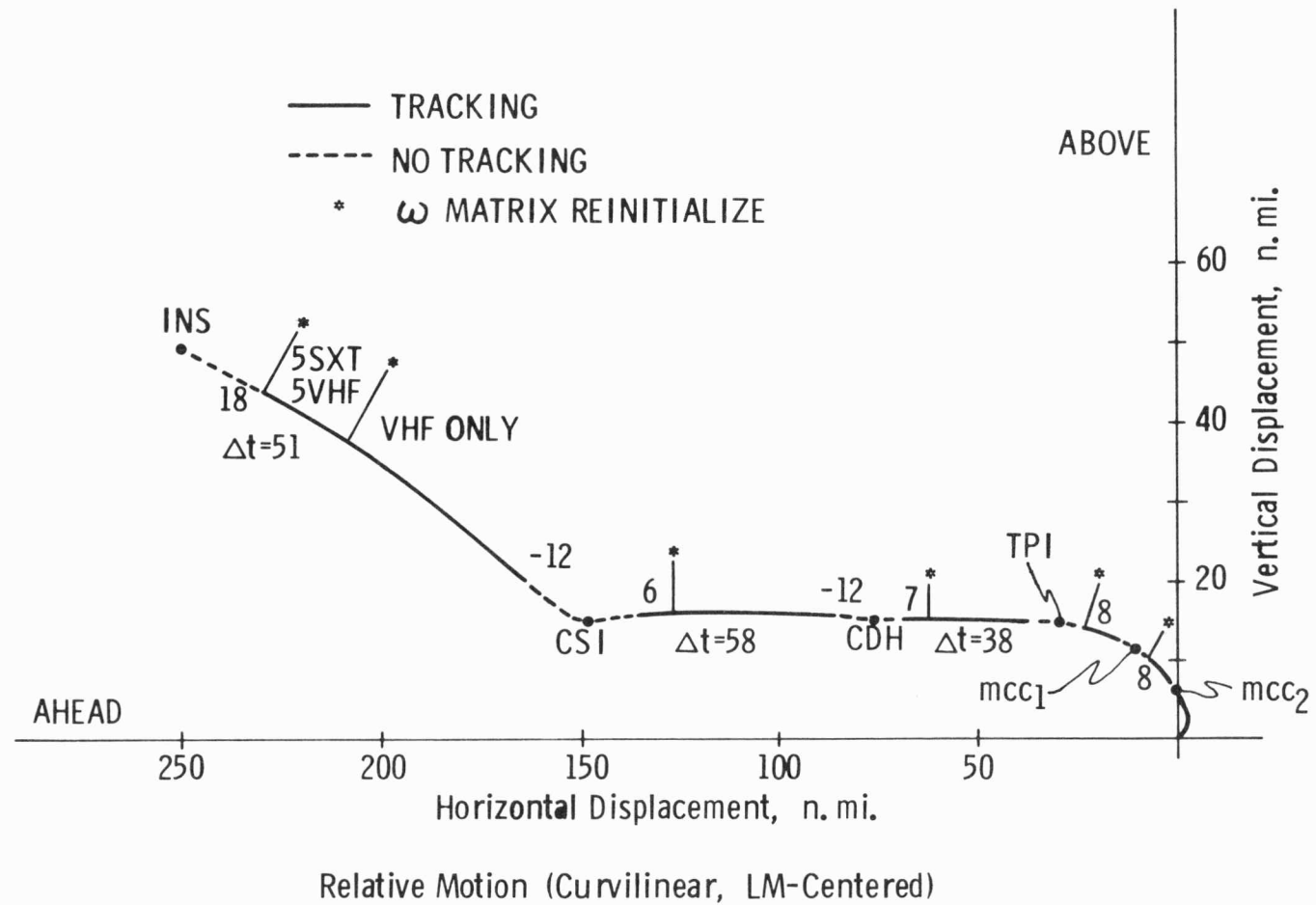


Figure 4.2.1-13. Typical Tracking Schedule for a CSM-monitored — LM-active Rendezvous

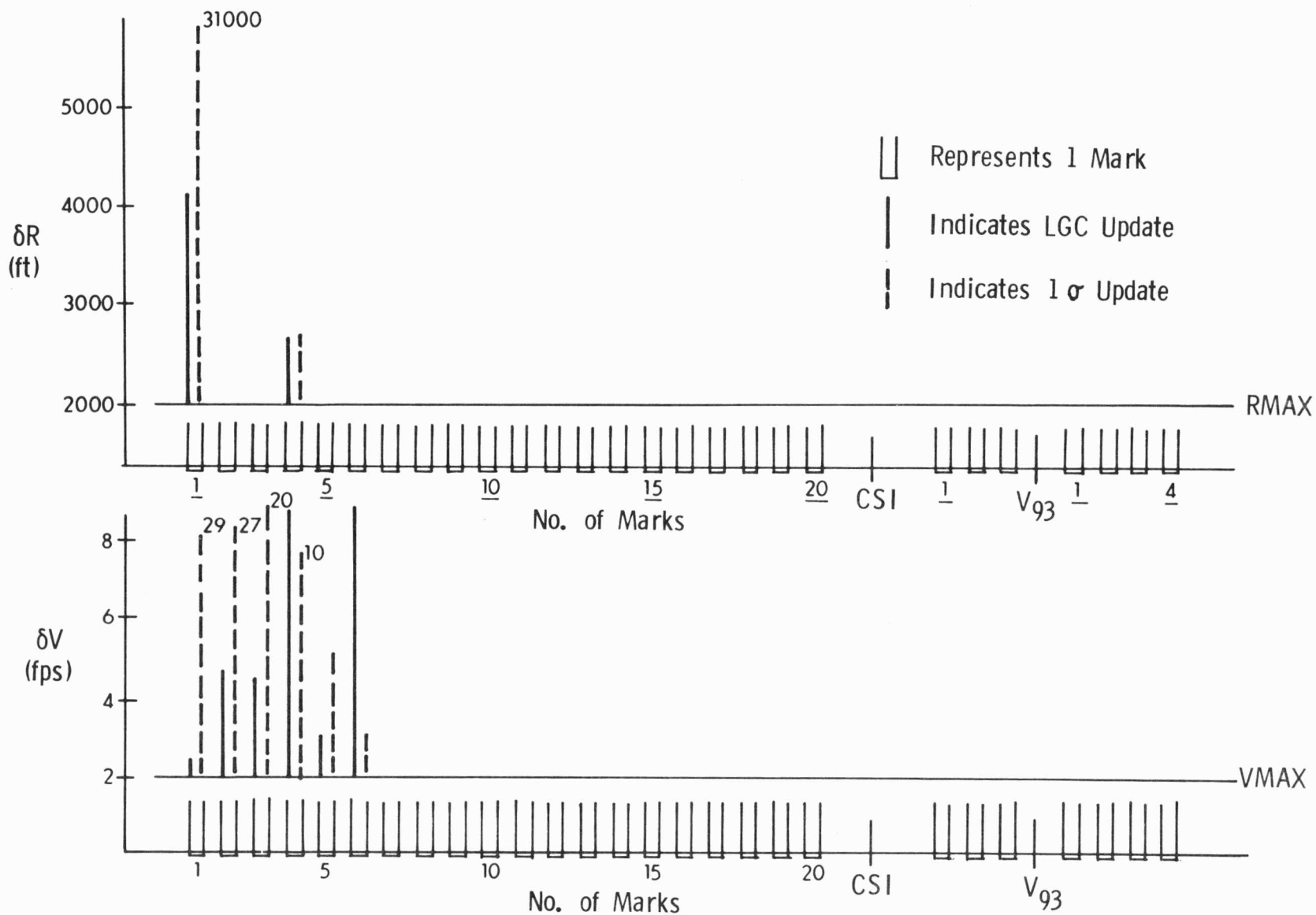
required optical measurements, and, by depressing the PRO key, return to the point departed from in the major program in progress. Similarly, the crew can call for VHF range data to be incorporated by selecting VERB 87 ENTR, which will allow range data to be incorporated until the crew resets the VHF RANGE flag, either by keying VERB 88 ENTR or by executing a program change (VERB 37). For marks to be incorporated, the UPDATE flag must be set. The flag is automatically reset during prethrust computations in order to protect erasable memory. The essential concern to the crew is that, except during P76 and during the VERB 06 NOUN 58 display in P34, marks can be incorporated during any targeting-program display preceding the crew's request for final targeting computation (PRO response to FL VERB 16 NOUN 45). A PRO to this display terminates navigation inputs to the targeting program. (See Section 5.0.) Figure 4.2.1-13 is a typical tracking schedule as would be furnished ahead of time by Mission Planning.

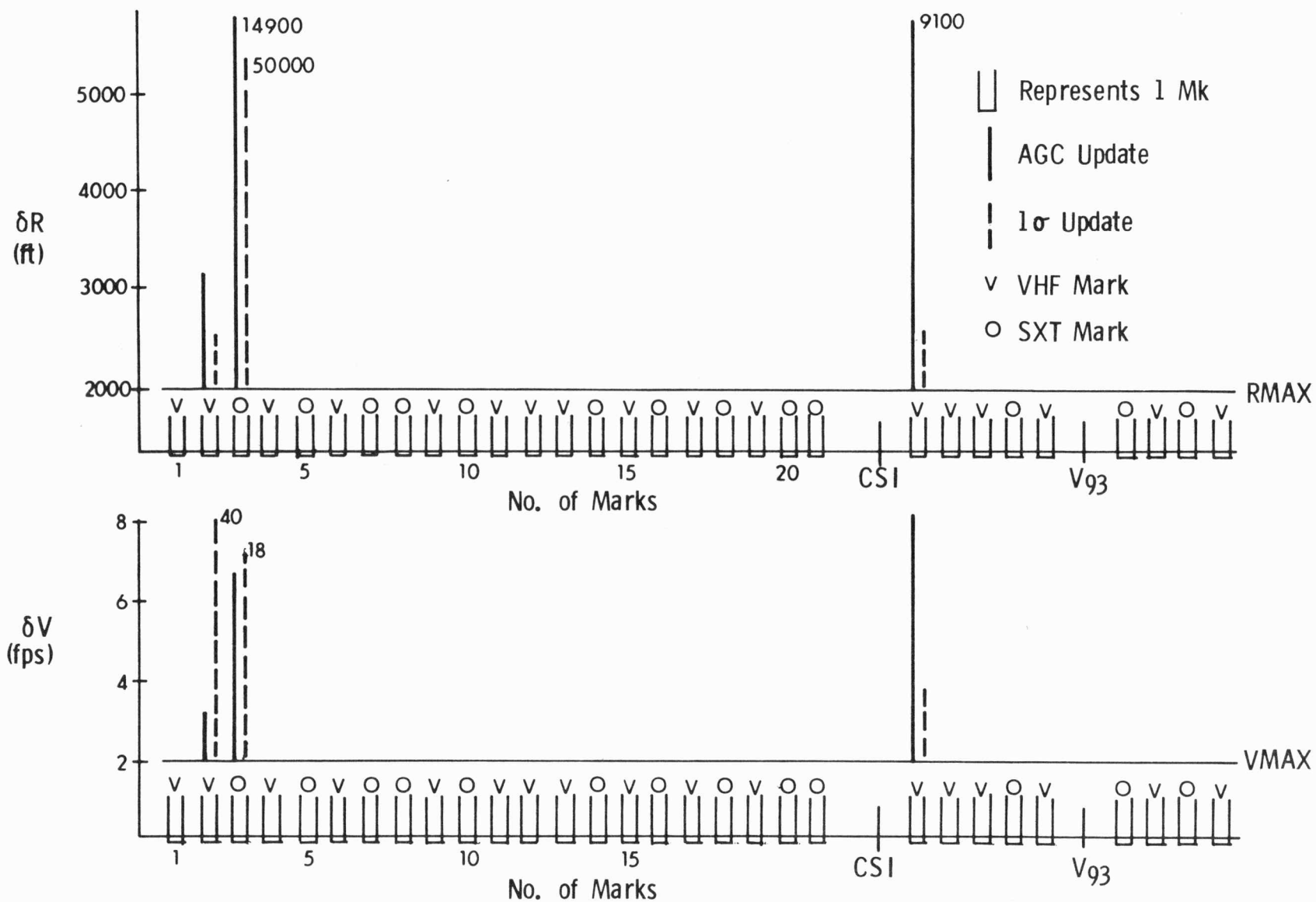
Although Mission Planning will give the times, number of marks, when to re-initialize the W-matrix, and what values to re-initialize to, there is a possibility that it would become necessary for the crew to extemporize its own tracking and re-initialization schedule. Accordingly, the following considerations for possible off-nominal conditions has been abstracted from E. Muller and P. Kachmar, Mission Simulation Memo 10-69, dated 12 May 1969.

Some general recommendations are made on mark-reject and accept procedures, as well as recommended procedures when state-vector updates indicate a divergent navigation solution. Two graphs (Figures 4.2.1-14, -15) present actual state-vector updates (that exceed R_{MAX} , v_{MAX} values) for an AGC and LGC bit-by-bit simulation of the nominal Mission F rendezvous. (Note: R_{MAX} , v_{MAX} limits were not exceeded after post-CSI V93.) Also shown are one-sigma state-vector updates.

The procedures here attempt to cover some off-nominal conditions. All off-nominal conditions, however, cannot be simply generalized; each case must be considered in the light of all information available; e.g., previous marking history may indicate a three-sigma radar, extremely large initial state errors that require a long tracking period to resolve, or degraded PIPA performance as evidenced by large state-vector updates after a burn.

4.2.1.5.1 State Vector Update. — The following are mission phases in which the largest state-vector updates can be expected:

Figure 4.2.1-14. Typical RR δR , δV Updates



- a. Initial period of tracking after insertion
- b. After maneuvers—either a burn for active vehicle or P76 for passive vehicle
- c. Beginning of tracking after long period with no tracking
- d. After W-matrix re-initialization.

Reasonable values for updates are a function of the phase in which they occur. Typically, a δr of 12000 ft and a δv of 12 ft/sec (before CSI), 5000 ft and 5 ft/sec after CSI, can be expected during phases of expected large updates. Should the update value seem excessive, the crew should reject the first mark, ensure that the sextant is actually tracking the LM, check VHF range against nominal, and repeat the mark. If the second mark yields a similar, or slightly larger, update, accept the mark and look for a decrease in the size of the update as marks continue. If update values do not become smaller, apply divergence procedure (paragraph 4.2.1.5.2 below).

Anomalous updates during "steady-state" conditions, i.e., not during phases of expected large updates, are in two categories:

1. Updates that are larger than the preset R_{MAX} , v_{MAX} but less than reasonableness criteria for phases of expected large update
2. Updates that are larger than reasonableness criteria, e.g., larger than 5000 ft and 5 ft/sec.

For the first category, the crew follow the same procedure described for larger-than-reasonable updates during expected-large-update phases. One bad mark could be the result of poor sighting technique or large random error. If anomalous updates continue, use divergence procedure (paragraph 4.2.1.5.2).

For the second category, assume a system failure and proceed as follows:

- a. Reject mark.
- b. If bias is suspected in VHF ranger, use divergence procedure.
- c. If three successive VHF marks and three successive sextant marks yield anomalous updates, use divergence procedure.
- d. If three successive VHF marks yield anomalous updates while sextant marks do not, inhibit VHF and use sextant alone.

4.2.1.5.2 Divergence Procedures. — There are six categories of anomalous conditions requiring special procedures:

1. Condition. State-vector updates are not decreasing (and are near the 12000 ft, 12 fps limits) after 10 accepted marks after insertion. Procedure. Re-initialize W-matrix; zero out bias estimates (not W-matrix bias loads). (Bias estimates apply only to the LGC.)

Implication. Initial relative errors were too large for initial W-matrix to handle; repeat entire procedure and if same results occur, assume system failure unless other vehicle is experiencing same difficulty. (This indicates ground uplink yielded relative errors of such a magnitude that system cannot resolve them.)

2. Condition. State-vector updates exceed R_{MAX} , v_{MAX} for three unaccepted marks during steady-state operation (where it is assumed a period of acceptable tracking precedes these marks). Procedure. Re-initialize W-matrix and accept first mark. If updates do not decrease after four or five accepted marks, system has failed.
3. Condition. State-vector updates exceed 5000 ft, 5 ft/sec for three unaccepted marks during steady-state operation (no excessive updates preceding as above). Procedure. Re-initialize W-matrix and accept first mark. If updates continue to exceed 5000 ft or 5 ft/sec, or do not decrease after four or five accepted marks, system has failed. If updates converge, realize that you may be operating with a sensor that has bias and that a state-vector error will exist. (The value of this error should be approximately the size of the first update after W-matrix re-initialization.)
4. Condition. Last mark before a maneuver exceeds R_{MAX} , v_{MAX} . Procedure. If you were in steady-state conditions before this, reject last mark. If updates were exceeding R_{MAX} , v_{MAX} before last mark, but were decreasing, accept mark.
5. Condition. Unreasonably large Position Update. Procedure. Reject; anything larger than $\frac{\text{range}}{5}$ can cause system to be unstable.

6. Condition. Unreasonably large update is accepted and is known to have been incorrect (system malfunction discovered; bad P76, bad ground uplink, etc.) Procedure. (A) Fix malfunction; (b) get new ground uplink, if possible, and start again; (c) if uplink not possible, re-initialize W-matrix to approximate position value of update, velocity value 0.001 x position value, zero out bias estimates (not in W-matrix load) and proceed. (Bias estimates apply only to the LGC.)

4.2.1.5.3—Summary of Correction Procedures for Anomalous Updates During Steady State Tracking.

1. Always check out sextant first—after a VHF mark and V88.
2. If both sensors fail procedure—V93 and start over.
3. If only one sensor fails procedure—proceed with other sensor only.

Sensor Verification (assumes first mark rejected)

$\Delta R, \Delta v(N49) < 1 \text{ n.mi.}, 5 \text{ fps}$	$\Delta R, \Delta v(N49) > 1 \text{ n.mi.}, 5 \text{ fps}$
accept second and third marks (PRO) if fourth mark under limit -- sensor data OK if fourth mark over limit-- sensor data bad	• reject three consecutive marks that exceed above limits (including first mark) (sensor data bad)

Recovery procedure after extremely large update known to be incorrect

- Record N49 value of ΔR (xxxx. x n. mi.)
- Terminate updates (V88)
- V67E, load N99 with
 - R1 = ΔR times 6000 (xxxxx. ft)
 - R2 = ΔR times 6 (xxxx. x fps)
 - R3 = +00001
- RESUME updates (V87)

4.2.2 P21, Ground Track Determination—CMC

P21 has two distinct uses. First, as P21 ground track determination, it can be used to predict marktaking opportunities for P22 orbital navigation. The astronaut specifies a time (GET) and vehicle (CSM or LM). The program integrates the appropriate vehicle state vector to that time, converts it into latitude, longitude and altitude, and displays the result. Second, with the latitude-longitude information returned by P21 and charts of the lunar terrain, landmarks can be identified in advance for marktaking. The altitude effectively determines the duration of the marktaking window.

An optional trajectory parameter display can also be obtained in P21 by using NOUN 73, which is useful during P23 cislunar coast and, in certain conditions in the vicinity of the moon, to determine the flight path angle (γ), at t_{IG} when using P37. (See paragraph 5.2.6.8.) NOUN 73 displays the altitude (range), velocity, and flight-path angle of the trajectory that results from extrapolating the current state vector of the CSM to some future time; e.g., LOI during the translunar phase and reentry time during the return.

Table 4.2.2-I lists the displays that occur in P21 with descriptions of the associated program features. Figure 4.2.2-1 is the program flowchart.

4.2.2.1 Options

The latitude, longitude and altitude predictions of future vehicle positions produced by the advanced ground tracking option in P21 can be used: 1) to select relevant portions of the lunar landscape on maps preliminary to making out-the-window landmark identification, and 2) to designate unknown landmark coordinates in P22 for auto optics acquisition. In lunar orbit, sufficient uncertainty is introduced into the vehicle state vectors by the current onboard potential model during extrapolation that coordinate predictions may contain errors of 1 or 2 n. mi. This presents no problem for option 1, but requires that probable state vector errors be taken into account for option 2. Variations in lunar gravity have a negligible effect at cislunar distances, so that the NOUN 73 option is accurate enough.

4.2.2.1.1 Advanced Ground Track Determination.—In near-earth or near-moon orbit, the astronaut can specify a future time to the program and have his coordinates (latitude, longitude, altitude) for that time returned. An optional recycle on the final latitude-longitude-altitude display will cause the program to return to the initial display where the desired time was input (VERB 06 NOUN 34) and return the time originally specified incremented by ten minutes. The astronaut can then PRO to obtain the LAT-LONG-ALT corresponding to the original GET plus ten minutes, or

TABLE 4. 2. 2-I

P21 GROUND TRACK DETERMINATION PROCEDURES

DSKY	Register	Comments
Key V37 E21E	DSKY P21	Only requirement for P21 is an up-to-date state vector. ISS not required.
FL V04 N06	R1 00002 R2 00001 R3 Blank	Vehicle code in R1=00002 =CSM R2=00001 indicates this vehicle; R2=00002 indicates other vehicle: Key PRO if correct; keying V22E will blank R2, permitting vehicle code to be changed.
FL V06 N34	R1 ooooo. hr R2 ooooo. min R3 oxx. xx sec	Request load desired GET (T-LAT-LONG) in hours, minutes, and seconds to nearest 0.01 sec. For present time set R1, R2 and R3 to all zeros. PRO to compute latitude, longitude, altitude for specified GET; V25E to change time.
FL V06 N43	R1 xxx. xx deg R2 xxx. xx deg R3 xxxx. x n. i.	Program displays vehicle latitude and longitude in degrees to nearest 0.01 deg in R1 and R2 (+is North or East, respectively) for specified GET. R3 contains altitude in nautical miles to nearest 0.1 n. mi. measured from launch pad radius (earth) or latest landing site radius (moon). V32E will increment T-LAT-LONG GET initially specified by 10 minutes; recycle to V06N34 display. T-LAT-LONG may then be overwritten via V25E to any desired time.
FL V37		Keying PRO will terminate P21.
Key N73E	R1 xxxxB n. mi. R2 xxxxx. fps R3 xxx. xx deg	Altitude to nearest 10 n. mi. Inertial velocity to nearest 1 fps. Flight path angle to nearest 0.01 deg. This display may be obtained in P21 any time after integration is complete.

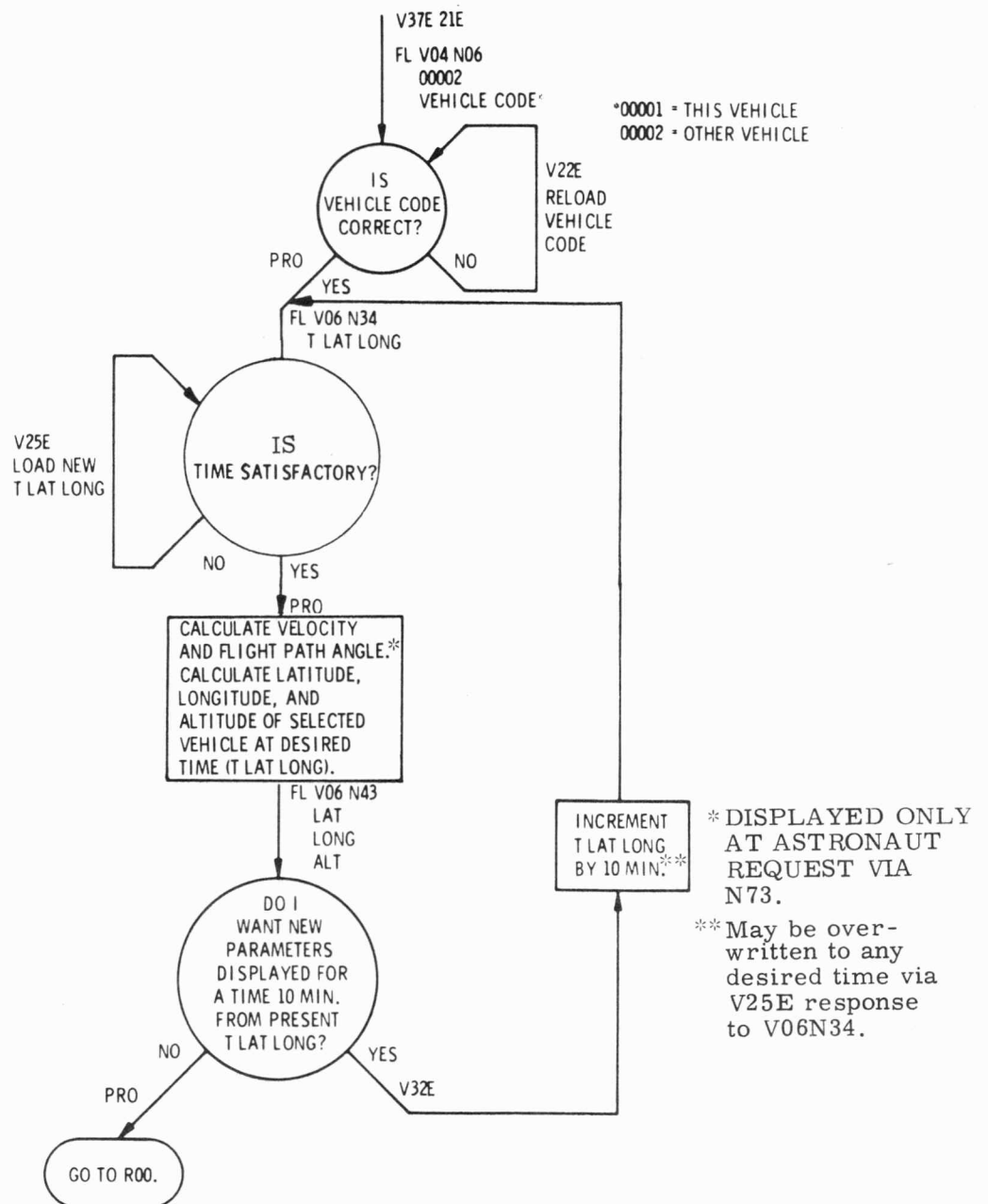


Figure 4.2.2-1. Ground Track Determination Program (P21)

reject it by keying VERB 25 ENTR and overwrite any desired T-LAT LONG. In this way he can identify particular landmarks available for P22 in advance and anticipate promising marktaking opportunities.

4.2.2.1.2 Orbital Parameter.—The P21 NOUN 73 option is primarily used after a P23 navigation sequence to determine whether the trajectory produced by the spacecraft's newly-updated state vector results in satisfactory terminal conditions at the target planet. Alternatively, the VERB 82 orbital parameters display (see P23, paragraph 4.2.4) can be called after the latitude-longitude-altitude display; i.e., after state-vector integration is complete. VERB 82 displays apogee and perigee height and time of free fall; this trajectory information supplements NOUN 73 and P37. (NOUN 73 is also used—in rare situations—to determine the value of γ for P37. See paragraph 5.2.6.8.)

4.2.2.2 Limitations

To predict the future orbital position of a vehicle (LM or CSM), P21 must obtain a precision integration of its state vector over the specified time interval. The further in advance the request is made (i.e., the larger the extrapolation interval), the less precise is the coordinate information returned. In earth or lunar orbit, the quality of the precision integration—and therefore the predictions—is determined primarily by the quality of the potential model used in the integration routine for the earth or moon gravitation.

On the first pass through P21, the program uses precision integration to compute the desired vehicle state vector at the specified T-LAT LONG. Computations for subsequent T-LAT LONGS via the VERB 32 ENTR option are conic and are based on the initial precision output. The CMC requires approximately 30 seconds to integrate one full revolution in lunar orbit. The recycle option will, therefore, perform quickly and precisely if the times chosen are close to the initial T-LAT LONG. If times input via VERB 32 ENTR differ significantly from the initial precision-integration value, the accuracy of the conic solutions obtained will degrade accordingly.

4.2.3 P22, Orbital Navigation—CMC

Table 4.2.3-I lists the purposes P22 was designed to achieve.

TABLE 4.2.3-I

PURPOSES OF P22 ORBITAL NAVIGATION	
1.	Locate and track a landmark suitable for navigation
2.	Obtain sighting marks on the chosen landmark
3.	Calculate the orbital parameter changes generated by the landmark sighting marks
4.	Display the orbital parameter changes generated by the first sighting mark on a landmark, for decision by the navigator/ground on the validity of the landmark and navigation process prior to incorporation of state vector changes resulting from the sighting marks
5.	Provide updated coordinates of the known landmarks
6.	Provide coordinates of unknown landmarks
7.	Track a preloaded landing site
8.	Provide coordinates of a new landing site (treated as an unknown landmark)
9.	Provide coordinates of an offset landing site
10.	Point the optics along an advanced orbit ground track for tracking and mapping a new landing site.

The onboard navigation and landmark mapping capabilities of P22 are not yet being used in the way originally intended, as optical marks are not processed onboard.* Items 2 and 7 are the only applications authorized. Optical marks are taken on the landing site and nearby known landmarks using state vector values and landmark coordinates supplied by the ground. A zero W-matrix is used and marks taken are not incorporated onboard but are downlinked for use in ground computations. Primary ground track data, together with downlinked optics marks are used to compute the spacecraft's state vector and acquisition orientation for the next marktaking sequence; these computations are uplinked shortly before they are required.

* This statement applies to the G and H missions and will probably remain valid until an adequate lunar potential model is obtained.

The program flowchart, Figure 4.2.3-1 delineates the decision points in P22; however, many of the optional paths are not significant at present.

Procedures that ensure proper landmark acquisition and marktaking are a precondition to successful landmark navigation using P22, whether marks are processed onboard or not. Because of the restricted use currently made of P22, the procedures in Table 4.2.3-II and the accompanying discussion (see paragraph 4.2.3.6) are concerned mainly with correct landmark acquisition and marktaking technique and not with evaluation of onboard updates, navigation, or mapping.

4.2.3.1 Program Options

The only live option in P22 at present is the choice between designating a known landmark which has its coordinates stored in the CMC (e.g., R2 equals 10001 for the landing site), or an unstored known landmark (R2 equals 10000), whose latitude, longitude, and altitude must be input by the astronaut. The latter option affords some flexibility in pointing the optics if there is any uncertainty in the landmark's true location. The IMU must be up and recently aligned since optics CDU angles recorded for each mark are referred to platform CDU angles. The quality of navigation data therefore depends directly on IMU alignment.

The program options that permit marks to be processed onboard, unknown landmarks to be mapped, and offset landing sites to be designated are not used.

4.2.3.2 Landmark Tracking Geometry

Figure 4.2.3-2 shows the geometry for tracking a landmark in a 60 n. mi. circular lunar orbit. Recommended marktaking technique requires that five marks be taken equally spaced over the plus-55- to minus-55-degree marktaking window. The advantage of oblique lines-of-sight on the first and last marks diminishes rapidly beyond ± 45 degrees. Consequently, marks taken symmetrically and at equally spaced intervals are preferred to marks taken asymmetrically at the extremes of the marktaking window. The interval between marks for the 76-degree (100-second) minimum marktaking window is 9 degrees (25 seconds); for the 110-degree (180-second) maximum window, the interval between marks is 27.5 degrees (45 seconds).*

* Illustrations and numerical data, MSC Internal Note No. 69-FM-81, "Lunar Landmark Tracking Attitude Studies," C. R. Hunt, TRW Systems, April 11, 1969.

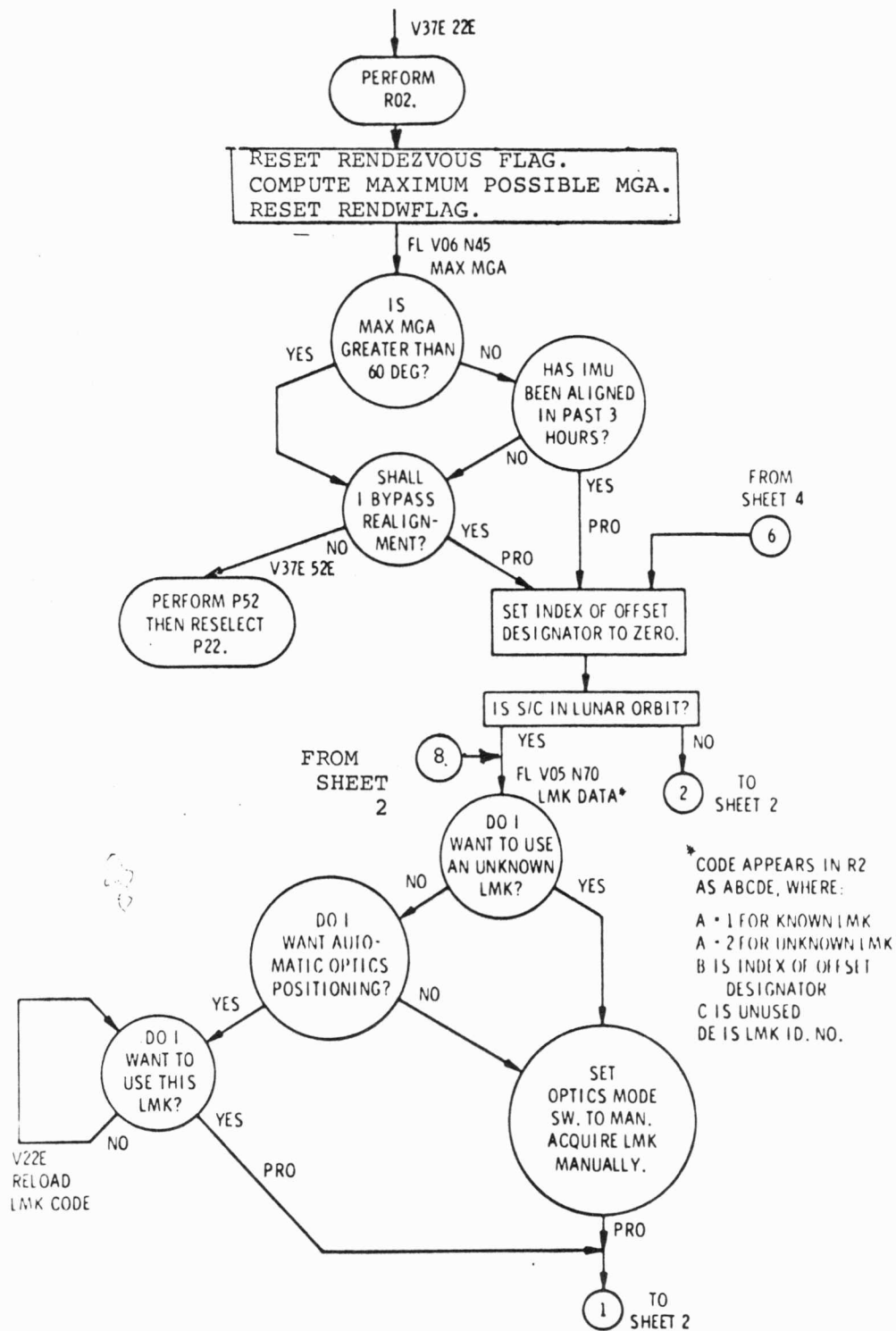


Figure 4.2.3 -1. Orbital Navigation Program (P22) (Sheet 1 of 4)

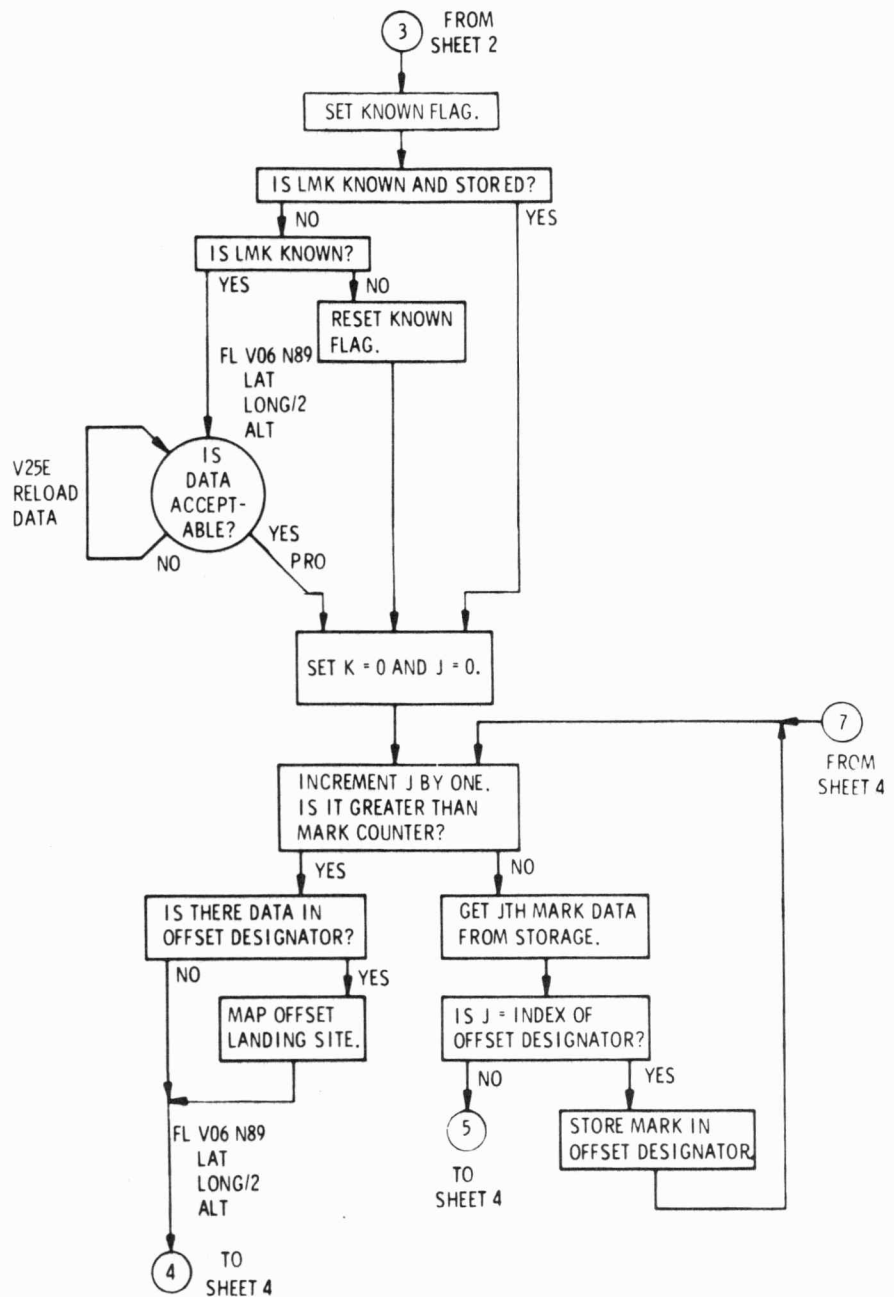


Figure 4.2.3 -1. Orbital Navigation Program (P22) (Sheet 3 of 4)

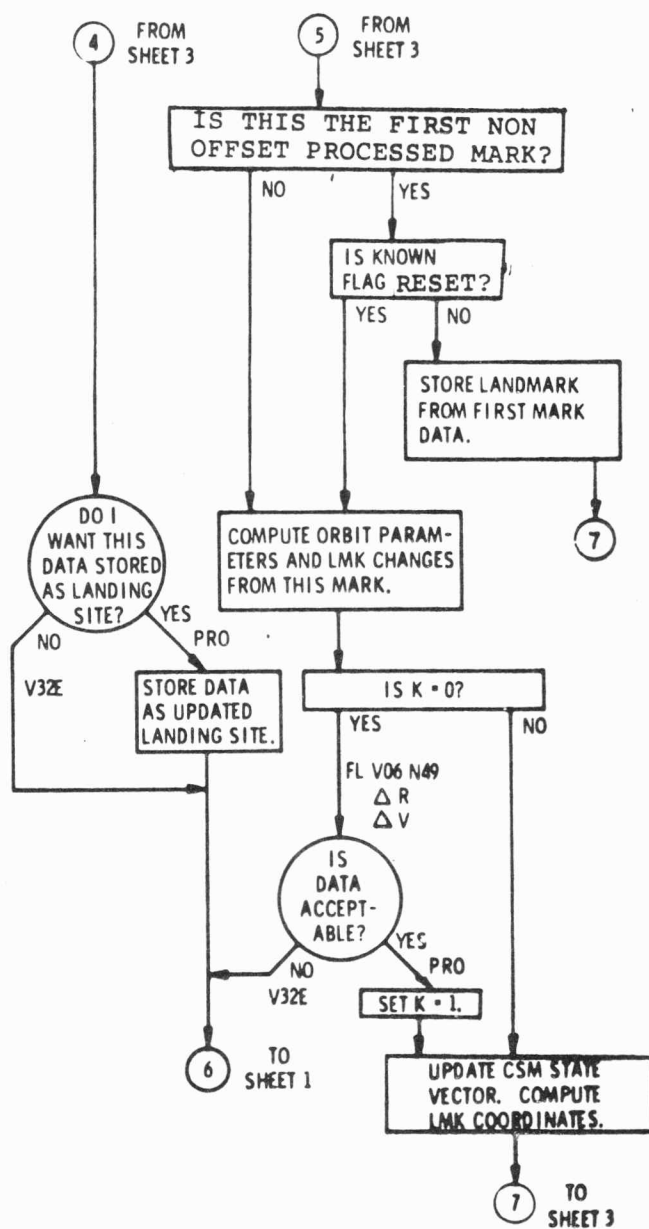


Figure 4.2.3-1. Orbital Navigation Program (P22) (Sheet 4 of 4)

TABLE 4.2.3-II
P22 PROCEDURES (SHEET 1 OF 3)

Step	DSKY Activity	Registers	Comments
1.	Key V37 E22E		P22 entered 5 to 10 minutes prior to point of closest approach. Note: Before entering P22, the SC will have been maneuvered to the acquisition attitude via VERB 49E. Optics may be driven to acquisition shaft and trunnion angles by keying VERB 41 NOUN 91E loading R1 and R2 with 00000°/55.000°.
2.	FL V06 N45	R1 Blank R2 Blank R3 oxx.xx	Maximum possible MGA to nearest 0.01 degrees (angle between \vec{Y}_{SM} and $\frac{\vec{V} \times \vec{R}}{ \vec{V} \times \vec{R} }$) is displayed. If angle is acceptable, PRO.
3.	FL V05 N70	R1 Blank R2 ABCDE R3 Blank	Key VERB 22E to select R52 auto optics option, load R2 with 10000 or 10001 and ENTR. A 1 signifies known landmark A 2 signifies unknown landmark B index of offset designator C not used DE landmark ID number PRO when correct values loaded. If optics were not driven to 0 degrees shaft and ~ 45 degrees trunnion before (See step 1), they can be positioned manually as follows: OPTICS ZERO - OFF OPTICS MODE - MANUAL Drive optics to 45 degrees with OHC and return OPTICS MODE switch to CMC
4.	FL V06 N89	R1 xx.xxx R2 xx.xxx R3 xxx.xx	Only appears if R2 = 10000, above. Latitude to nearest 0.001 degree, + is North. Longitude divided by 2 to nearest 0.001 degree, + is East. Altitude above Fischer Ellipsoid or mean lunar radius to nearest 0.01 n.mi. Load DAP via V25N79E (step 5) in preparation for maneuver in step 6. PRO on re-appearance of N89 when DAP is loaded.

TABLE 4.2.3-II
P22 PROCEDURES (SHEET 2 OF 3)

Step	DSKY Activity	Registers	Comments
5.	FL V25 N79	R1 x.xxxx R2 xxx.xx R3 xxxxx	SC rate in deg/sec to nearest 0.0001 deg/sec. + for increasing CDU angles. SC deadband to nearest 0.01 deg. Axis code 00000 = X-axis (roll) non-zero = Y-axis (pitch). Key VERB 25E and reload DAP data . Recommended loads are: R1 = -00500E for -0.05 deg/sec pitch rate (-02000 or -03000 for -0.2 or -0.3 deg/sec rates). R2 = +01500E for 15 deg deadband R3 = +00001E to pitch about Y control axis (any non-zero number). Reappears when N79 data ENTR keyed. PRO to step 6.
	FL V06 N89		
6.	V06 N92	R1 xxx.xx R2 xx.xxx R3 Blank	Shaft angle to nearest 0.01 degree. Trunnion angle to nearest 0.001 degree. R52 will drive optics angles to point at landmark: If trunnion angle exceeds 50° limit, 407 PROG alarm will occur. (Although unlikely, 00404 alarm will flash if T angle exceeds 90°). S and T angles will continue to be displayed though, and the alarm can be reset when the trunnion comes within 45°. Optics will then track automatically. The VERB 06 NOUN 92 display will not appear unless the OPTICS ZERO switch is OFF and the OPTICS MODE switch is in the CMC position. Landmark should be acquired and confirmed before pitch down point. At CPA -90 sec, key VERB 79E to obtain NOUN 79 (step 5). If DAP loads are correct, PRO to initiate pitch rate. NOUN 79 display (step 5) will not appear and VERB 06 NOUN 92 display will freeze without KEY RELEASE, though PRO will still initiate the maneuver, after which VERB 06 NOUN 92 will reappear. When marktaking window is entered and astronaut is ready to track manually switch Optics Mode to MAN and initiate manual tracking with OHC.

TABLE 4.2.3-II
P22 PROCEDURES (SHEET 3 OF 3)

Step	DSKY Activity	Registers	Comments
7.	FL V51		R53 Sighting Marks Routine is selected by switch to MAN and VERB 51 Please Mark request will flash until 5 marks are taken. Mark Reject button will erase last mark data and decrement mark counter.
8.	FL V50 N25	R1 00016 R2 Blank R3 Blank	Terminate mark sequence flashes after fifth mark. PRO will return to P22.
9.	FL V05 N71	R1 Blank R2 ABCDE R3 Blank	Same as V05 N70 measurement ID, confirm and PRO.
10.	FL V06 N49	R1 xxxx.x R2 xxxx.x R3 Blank	DELTA R } In n.mi. to nearest DELTA V } 0.1 n.mi.; in fps to nearest } 0.1 fps Hold for 11 seconds and PRO (W-matrix is zero so both DELTA R and DELTA V will be zero).
11.	FL V06 N89	R1 xx.xxx R2 xx.xxx R3 xxx.xx	Same as step 4, confirm and V34E Latitude to nearest 0.001 degree; + is North Longitude divided by 2 to nearest 0.001 degree;+ is East Altitude above Fischer Ellipsoid or mean lunar radius to nearest 0.01 n.mi.
12.	FL V37		Return to CMC auto. V34E keyed above terminates P22 and causes V37 to flash after processing delay.
13.	00E		00E response to FLV 37 transfers to R00

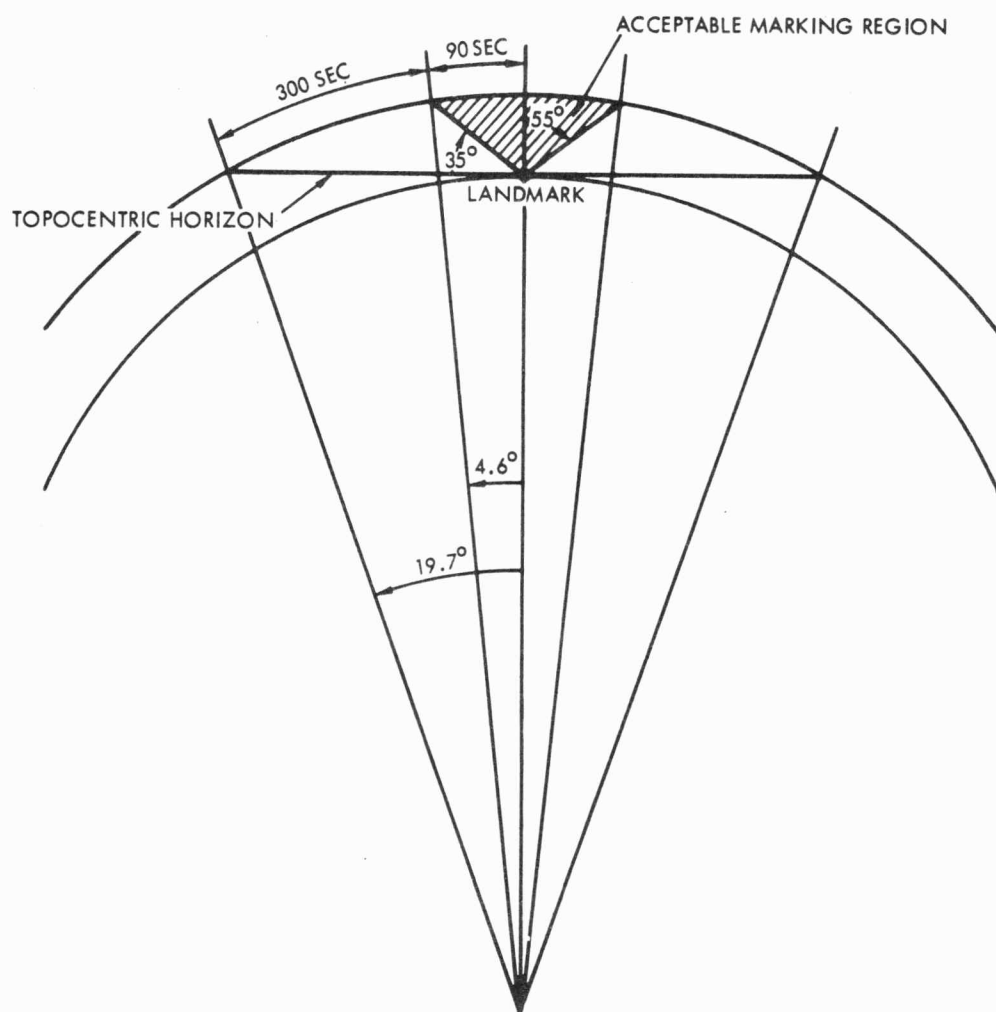


Figure 4.2.3 -2. Landmark Tracking Geometry for a 60-Nautical Mile Circular Lunar Orbit

4.2.3.2.1 Landmark Tracking Modes.—Two landmark tracking modes have been defined which, with variations and in combination, suffice to define all practicable landmark tracking possibilities.* Mode I is used for landmark tracking in the CSM/LM docked configuration when the LM blocks portions of the CSM SCT and SXT FOV. (See Figure 4.2.3-3.) An area of diminished brightness, similar to the one shown for the SCT, also exists for the SXT. However, the lunar landscape is sufficiently bright that the total FOV of both instruments is assumed to be useful for landmark tracking. Mode I requires that the CSM/LM combination be maneuvered—well before marks are taken—to an inertial attitude that becomes -2 degrees nosedown with respect to the local horizontal at the 55-degree start of the marktaking window. This position affords a good angle of forward vision for acquisition.

Figure 4.2.3-4 illustrates the geometry for Mode I landmark tracking. The landmark enters the SCT FOV 148 seconds before the closest point of approach (CPA) to the landmark at an elevation angle of 21 degrees; it enters the SXT FOV 112 seconds before the CPA at an elevation angle of 28.2 degrees. At 90 seconds before CPA and 35 degrees elevation angle, the spacecraft X-axis reaches the predetermined -2.1-degree attitude with respect to the local horizontal, and a -0.3 deg/sec pitch rate is started.** This causes the vehicle and the optics shaft axis to rotate through -54 degrees while traversing the 180-second (110 degree) marktaking window.

The -2.1-degree attitude allows 58 seconds and 22 seconds for acquisition in the SCT and SXT, respectively, before the pitchdown rate is initiated. The landmark will remain in the SXT FOV throughout the acceptable marking region, even if the pitch rate is slightly less than 0.3 deg/sec or if its initiation is slightly delayed.

A variant of Mode I calls for an 8-degree nosedown attitude at the 90-sec/35 degree pitch down point, plus a -0.2 deg/sec rate. With this version, the landmark enters the SCT FOV 38 seconds before the pitch is initiated, and enters and leaves the SXT FOV at almost exactly the 55-degree boundaries of the marktaking window, leaving almost no margin for error.

* Actually four modes were defined in the Hunt Study but Mode II is a combination of Modes I and III and Mode IV is a roll mode not currently practiced for P22.

** This same inertial attitude is equivalent to +2.5 degrees at the landmark local vertical.

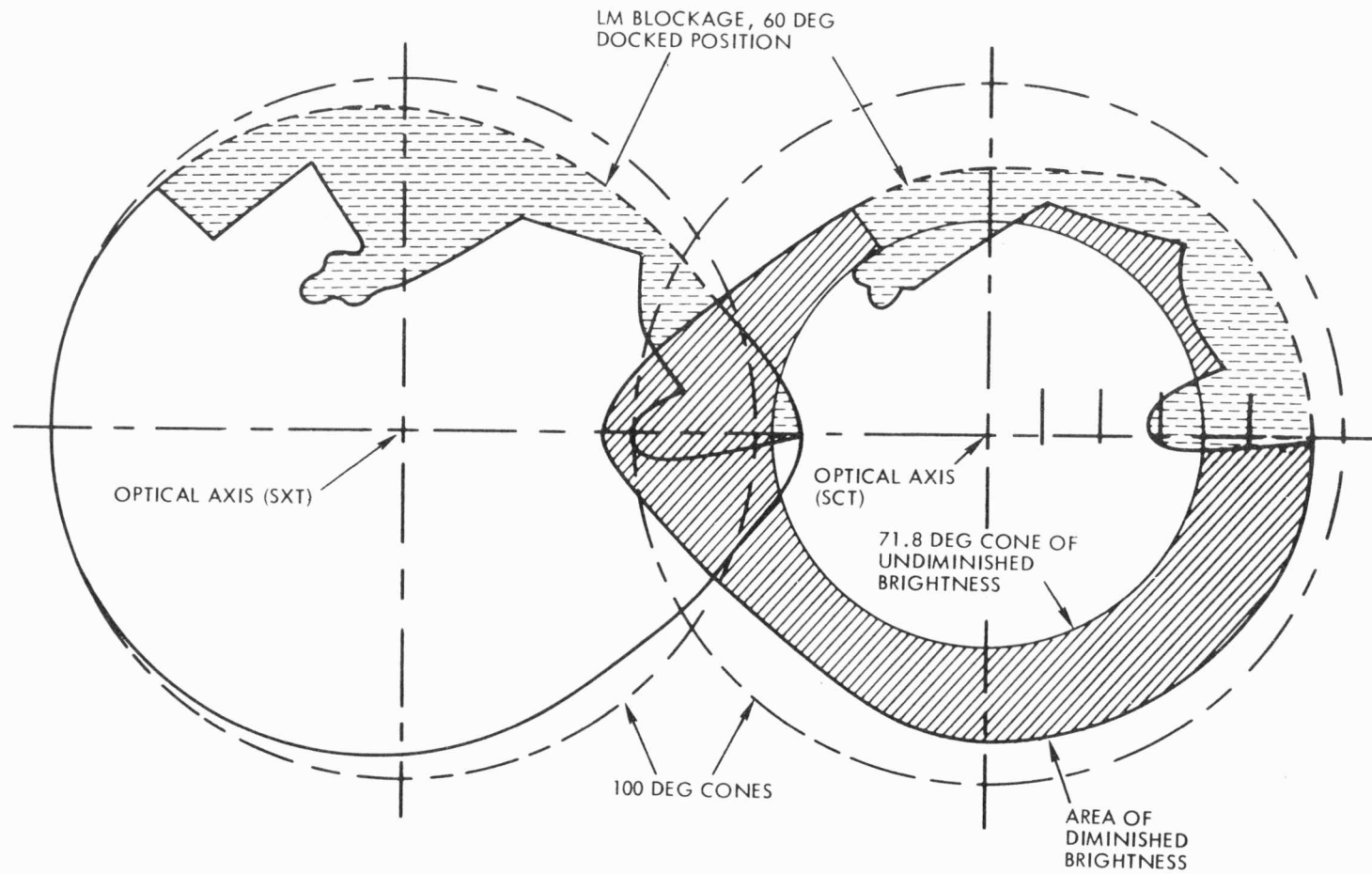


Figure 4.2.3 -3. SXT and SCT Fields of Coverage

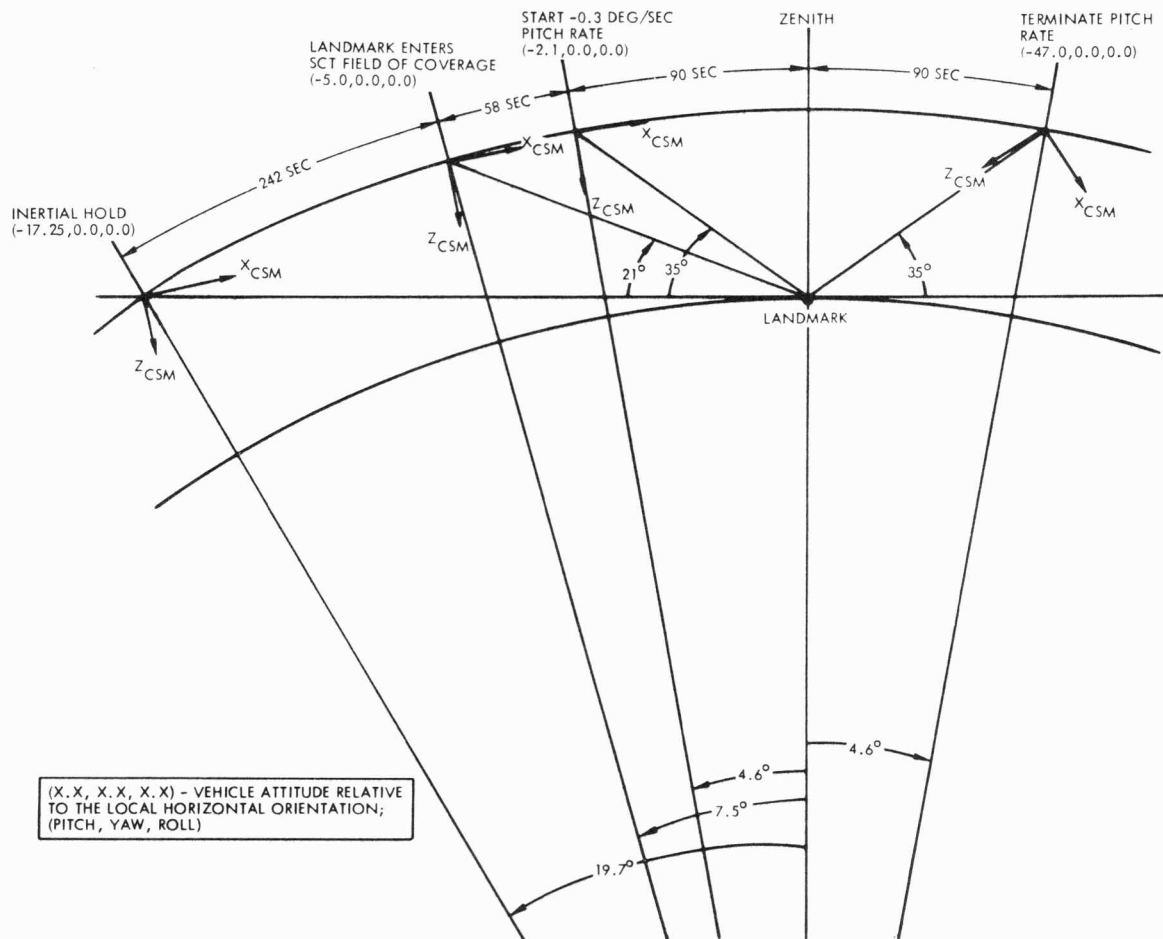


Figure 4.2.3 -4. Tracking Geometry for Mode I Landmark Tracking

Mode III is used after separation when the LM no longer blocks the CSM optical FOV. This mode consists of a -22-degree nosedown local attitude hold, accomplished by maneuvering the spacecraft X-axis 22 degrees below the local vertical and immediately initiating a 0.05 deg/sec negative (orbrate) pitch rate, which effectively maintains the spacecraft attitude constant at 22 degrees below the local horizontal. Figure 4.2.3-5 shows the elevation angles and times a landmark will enter the SXT and SCT FOV and exit the SXT. In Mode III, 5 or 10 degrees of the marktaking window after CPA is traded for 30 to 60 seconds of acquisition time, i.e., pre-mark tracking of the landmark. Mode III orbrate tracking is the standard undocked landmark tracking method because it requires the minimum feasible pitchdown rate and, therefore, minimizes RCS fuel use. The important variable in Mode III is the choice of an optimum amount of nosedown attitude.

In the G-mission, visual acquisition and identification of landmarks through the spacecraft windows proved relatively easy. It is still a problem, however, to find landmarks using the SXT—with its narrow field of view—when auto optics pointing information contains significant errors. An appreciable noseup acquisition attitude seems necessary if time is required to scan large areas using the SXT with its 1.8-degree FOV. In situations where the target is a terrain feature and not the LM, optical acquisition in the SCT would appear to be a good possibility. If feasible, acquisition via the SCT might allow a few degrees more negative acquisition attitude, so that 30 seconds of acquisition time could be exchanged for a full post-zenith marktaking window.

4.2.3.2.2 Optical Tracking Rate Limitations.—Implicit in the foregoing discussion of acquisition attitudes and tracking rates is the assumption that both the spacecraft X-Z plane and the landmark are in the orbital plane. This is not so. If the landmark is in the orbital plane, the spacecraft must be rolled out of the orbital plane to prevent excessive shaft rates that would result if the LOS to the landmark were permitted to pass within a few degrees of the shaft.

At the closest point of approach, the trunnion rate goes to zero for an instant and the shaft must rotate at the actual LOS rate times the cosecant ($1/\sin$) of the roll angle. If the roll angle is small, the cosecant may be very large and the maximum shaft rate correspondingly high, e.g., the shaft rate approaches infinity as the off-axis angle approaches zero. A 10-degree roll angle gives about six times the approximately 5/6-deg/sec LOS rate. At 60 n. mi., this produces a shaft rate of 5 deg/sec, well within the 15 deg/sec shaft drive rate limit.

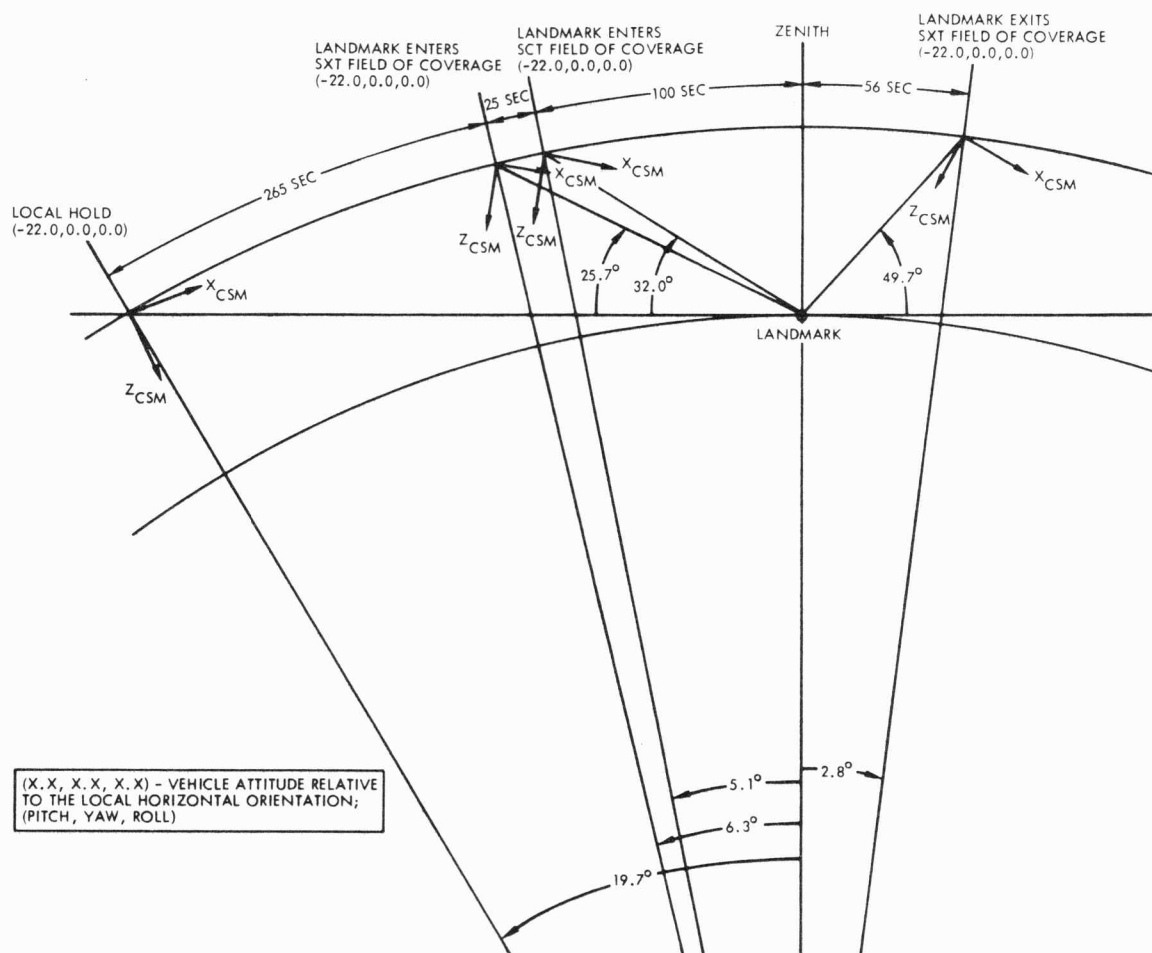


Figure 4.2.3 -5. Tracking Geometry for Mode III Undocked Landmark Tracking

The 10-deg roll is positive (right) since this rotates the optics FOV into the less obstructed quadrant of the CSM FOV occulted by the LM before separation (see Figure 4.2.3-3), and more nearly conforms with the 7.25 degree X CDU constraint for the Barbecue Mode Routine. (See paragraph 4.2.3.3.) If the landmark is off the ground track appreciably (particularly between 4 degrees and 16 degrees to the left at the groundtrack), the roll angle must be modified accordingly. The resulting roll angle must compromise the requirement that the shaft axis be more than 6 degrees from the landmark LOS at CPA with the yaw that will result from rolls other than 7.25 degrees.

4.2.3.3 Acquisition Attitudes and Marktaking Pitch Rates

The principal decisions that must be made in P22, as it is currently used, are the selection of the extended verbs and routines required to obtain the desired attitude and pitch rate—with particular emphasis on the timing and magnitude of rates and maneuvers. The two fundamental tracking modes, with several variations, involve various combinations of vehicle attitude and pitch rate, depending on whether marks are to be taken in the docked or undocked configuration and on the size of the acquisition and marktaking windows required.

Maneuvers to inertial acquisition and tracking attitudes can be performed using the Crew Defined Maneuver Routine, R62, obtained by keying VERB 49.

Pitch rates can also be applied using the RHC in the acceleration command mode. Alternatively, after the landmark has been acquired, the Minimum Impulse Controller can be used, in the CMC FREE position to impose a pitch rate prior to marktaking.

Attitude rates can be obtained by a number of alternative methods. Orbrate (-0.05 deg/sec) can be attained by loading a minimum rate into the DAP and commanding a maneuver to an attitude sufficiently far (e.g., 45 degrees) from the initial attitude that it will not be reached during the marktaking interval, so that the vehicle will continue to pitch at orbrate while the landmark is acquired and marks are taken.

The Barbecue Mode Routine (R64) which is called by VERB 79 ENTR is now available and permits pitch rates to be applied automatically. However, the use of this routine is limited. The major limitation is that the roll angle must be approximately 7.25 degrees to align Y_{SC} with Y_{SM} . [To the extent that a roll angle other than 7.25 degrees is required (viz., 10 degrees; see paragraph 4.2.3.2.2), any pitch rate applied with VERB 79 will couple a component of the pitch rate proportional to the sine of

the difference angle (e.g., $10 \text{ deg} - 7.25 \text{ deg} = 2.75 \text{ deg}$) into a yaw maneuver. For landmarks within a few degrees of the groundtrack this effect is negligible.]

Another limitation is that R64 must be called after initiation of P22 because new program initiation stops the orbital rate.

4.2.3.4 Preliminary Procedures

The IMU is aligned via P52 as near to the time landmark tracking begins as is convenient—usually about 1 hour before P22 is entered. The landing site alignment used is that in which the stable member X-axis is aligned to the landing site local vertical. To obtain the 22-degree nosedown, 10-degree left roll acquisition attitude defined above, key VERB 49E and load R1, R2 and R3 in the NOUN 22 display with 10 degrees, 248 degrees and 0 degrees, respectively (248 degrees represents a 112-degree pitch down from the landmark local vertical).

In the H1-mission, the attitude required for acquisition will be computed and the P22 PAD voiced up immediately before the VERB 49 maneuver to the acquisition attitude. In the G-mission the maneuver PAD was transmitted 45 minutes to an hour ahead because the landing site was farther east and there was insufficient time for tracking and computation of new PAD values before the maneuver. For westerly landing sites, the CSM can be tracked through the period after communication is reestablished, less than an hour before the maneuver. In this way state vector information with the smallest possible extrapolation and potential modeling errors can be incorporated into the computed VERB 49 roll, pitch and yaw values.

4.2.3.5 P22 Acquisition and Marktaking Procedures

The VERB 49 maneuver to the inertial hold attitude that produces the -2.1-degree attitude specified at the -90-second pitchdown point (Figure 4.2.3-4), can be performed 10 minutes or more in advance.* This allows time to enter P22 early, proceed to the NOUN 89 LAT-LONG display, set up the automatic pitch maneuver with VERB 79, and return to P22 to monitor auto optics tracking of the landmark via the VERB 06 NOUN 92 shaft and trunnion displays. At 90 seconds before CPA, or before, if visual acquisition has occurred, VERB 79 is recalled and the pitch maneuver initiated using a 6-keystroke sequence. The landmark is being tracked

* The convention in the illustrations (pitch, roll, yaw) is not consistent with the roll, pitch, yaw convention used in loading R1, R2 and R3 in VERB 49, and also omits the 10-degree roll, and the use of inertial landmark local vertical coordinates.

meanwhile by auto optics and monitored with the SXT by the astronaut. With a -0.3 deg/sec pitch rate, the vehicle angular rate very nearly matches the LOS rate at $+55$ deg (0.34 deg/sec) so that a switch to the MANUAL optics mode at this time requires relatively little initial intervention with the OHC by the astronaut.

If P22 is entered much before the spacecraft reaches the topocentric horizon (landmark local horizontal, which at 60 n. mi. always occurs 6-1/2 minutes before CPA) a 00407 program alarm will occur signifying that the trunnion angle is greater than 50 degrees. At -17.25 degrees below the local vertical, the spacecraft X-axis is 2.5 degrees above the landmark horizon, which is where the trunnion angle reaches 50 degrees. The program continues to compute and display the angle during the alarm, and when the DSKY value in R2 falls below 45 degrees, the alarm can be reset and R52 will drive the optics to the computed shaft and trunnion angle values. Before entering P22, the astronaut may pre-position the optics at 0 degrees shaft and 45 degrees trunnion by keying VERB 41 NOUN 91E and loading R1 and R2 with 00000 and 45.000, respectively, thereby saving the 3 or 4 seconds required to drive them there at acquisition time.

4.2.3.6 Restrictions and Limitations

Two incompatible combinations must be avoided when using VERB 49 and VERB 79 with P22. An erasable location is shared by VERB 49 and VERB 79, so that any attempt to set up a pitch rate in VERB 79, and then to perform a maneuver using VERB 49 and return to VERB 79 will find the desired DAP data overwritten by VERB 49. Any maneuver using VERB 49 after setting up the VERB 79 pitch rate, therefore, requires that the VERB 79 DAP data be reinitialized. The pilot must always verify that NOUN 79 is properly loaded before initiating the pitch rate.

Ideally, NOUN 79 would be loaded prior to entering P22, and the order of performance would be: maneuver to acquisition attitude (VERB 49); initiate orbrate (VERB 79); and enter P22. However, in Mode I (where the inertial attitude is held until the landmark is acquired before the pitch rate is initiated), P22 will perform R00 which will overwrite the VERB 79 DAP data. And in Mode III, R00 will kill the orbrate if it is initiated prior to P22. The procedure outlined in Table 4.2.3-II is therefore recommended for both modes. The shaft and trunnion acquisition angles and alarm limits are different for the two tracking modes and the timing and amount of the pitchdown rates change.

4.2.3.7 Alarms

A list of alarms that may be encountered in P22 and an explanation of each follows:

- 00210 Alarm — IMU not on
- 00220 Alarm — IMU orientation not known
- 00120 Alarm — Optics not zeroed
- 00116 Alarm — Optics taken out of zero before 15 seconds elapse
- 00115 Alarm — Optics torque request with mode switch not at CMC
- 00404 Alarm — Trunnion angle exceeds 90 degrees. (See Table 4.2.3-II.)
- 00407 Alarm — Trunnion angle exceeds 50 degrees. (See Table 4.2.3-II.)
- 31211 Alarm — Illegal interrupt of extended verb which occurs if optics MODE switch is switched to MAN when VERB 79 has been called, but not executed.

4.2.4 P23, Cislunar Navigation—CMC

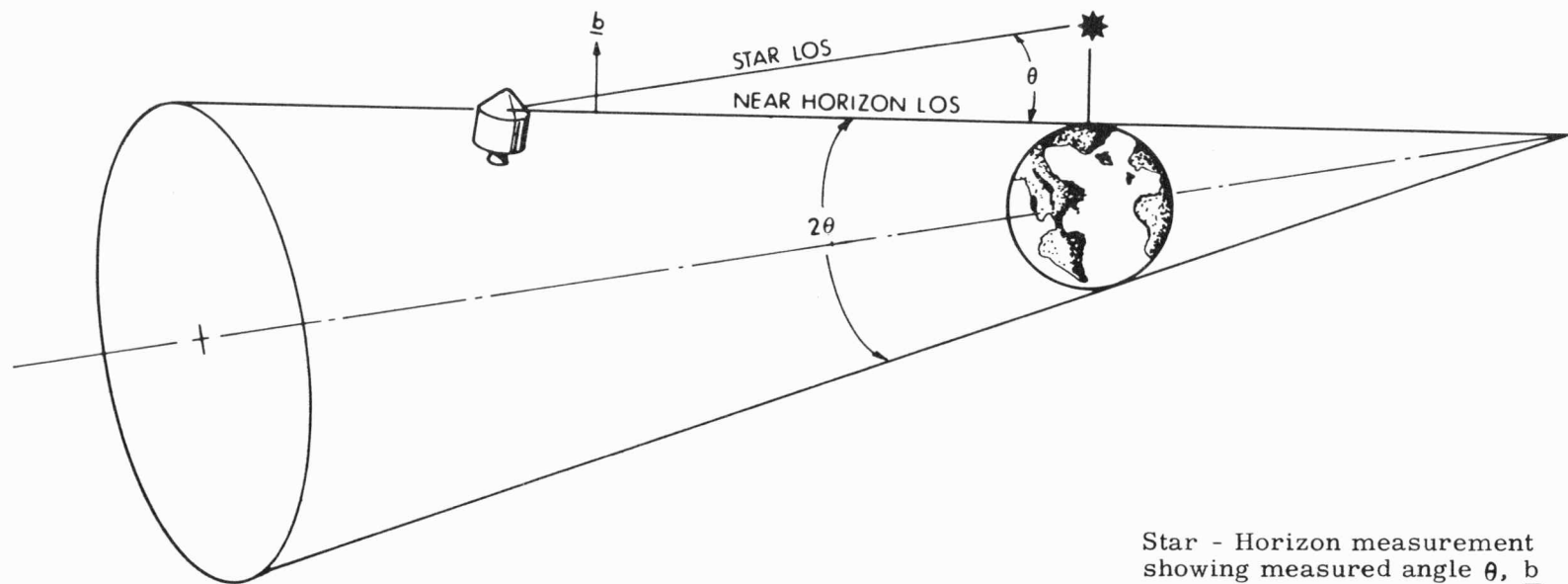
Program P23 permits navigation fixes to be made during translunar and transearth coast. These fixes are made through updating the spacecraft state vector by measuring the angle between a suitable star and an earth or lunar horizon or lunar landmark. (See Figures 4.2.4-1a and b.) The resulting position and velocity data provide the basis for onboard targeting of nominal translunar and transearth trajectories, time-critical aborts, and free returns should communications fail. Navigation using P23 is feasible within either the earth or the lunar gravitational sphere.*

Figure 4.2.4-2 shows the schedule of P23 activity for the G-mission plotted on a diagram of the translunar and transearth trajectories. Fifteen state vector updates were scheduled in all—two early in translunar coast and thirteen at intervals throughout the transearth return. Three marks were specified on each of three to five stars for each update, each mark requiring an individual P23 entry. In all, cislunar navigation during G-mission transearth coast entailed 177 performances of P23, producing a total of 177 marks on 59 stars. (Notice that one star in each sequence was usually marked on twice.) The figure gives the nominal time of each sequence of P23 activity, the decimal star code of each 3-mark star-horizon measurement in the sequence, three initials (e.g., NEH, FEH, signifying near-earth horizon and far-earth horizon, respectively; NMH, FMH, signifying near-moon horizon and far-moon horizon) and the times of the three midcourse corrections that would have been computed onboard using P37 had communications failed. (Note that before taking measurement marks and at half-hour intervals while marks are being taken, it is necessary to calibrate the SXT optics to compensate for measurement errors due to trunnion bias.)

Nominally, sets of three marks are taken on successive stars at 10-minute intervals, allowing ample time for maneuver and optics pointing. The three redundant marks made on each star provide a sounder statistical basis for measurement incorporation than single marks. Two marks will work almost as well if three are inconvenient; five are recommended on the first star marked after a sleep period or after TEI when errors may be large.

The two sequences of P23 activity at 06:30 GET and 24:30 GET during the translunar phase are, in effect, rehearsals that obtain data on the consistency of the navigator's

* Since P37 makes use of the state vector data compiled by P23, it is noteworthy that P37 requires a t_{IG} outside the lunar sphere.



Star - Horizon measurement showing measured angle θ , \underline{b} vector and measurement cone of revolution, 2θ , for (a) near-horizon and (b) far horizon geometry

Figure 4.2.4-1a. Star Horizon Measurement Geometry (Near-Horizon)

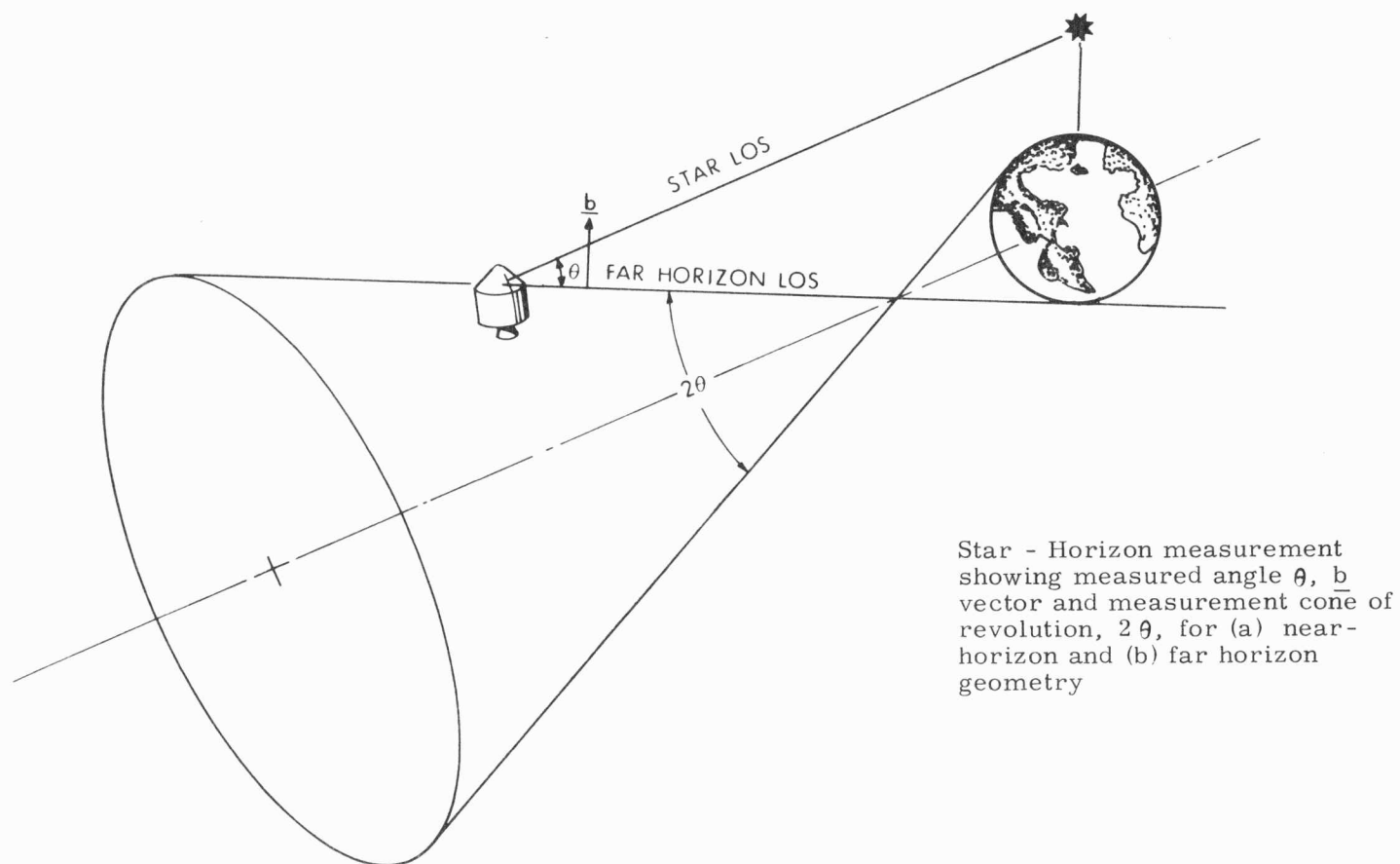


Figure 4.2.4-1b. Star Horizon Measurement Geometry (Far-Horizon)

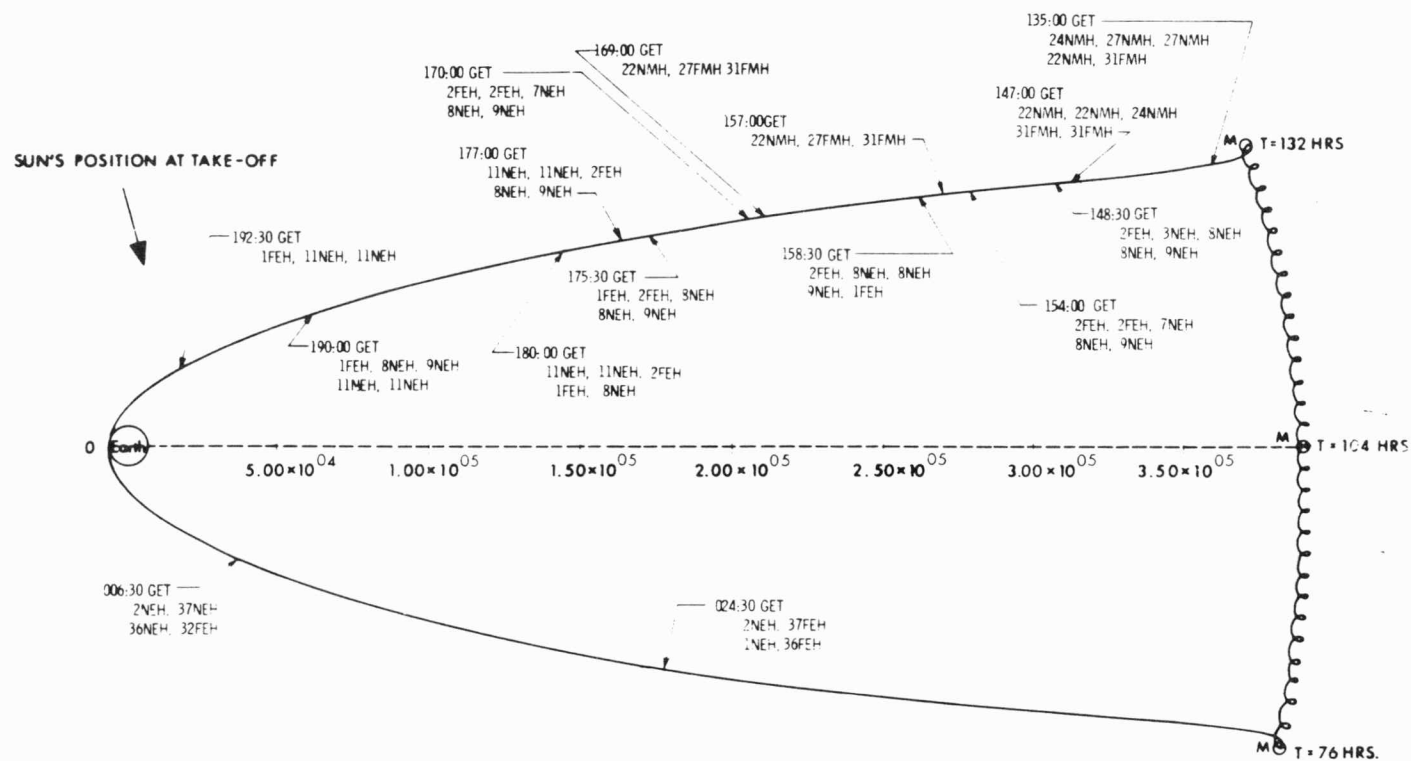


Figure 4.2.4-2. P23 Activity for G-Mission Translunar and Transearth Trajectories

subjective perception of the earth horizon (i.e., its variance and any bias as a function of range) and star visibility thresholds. These preliminary translunar P23 data are downlinked and analyzed to refine a priori statistical variance which is subsequently stored in the CMC via uplink for use during the transearth cislunar-navigation phase.

Figures 4.2.4-3a and b show two views of earth that illustrate the available measurement stars visible in the 60-deg FOV of the SCT at the respective 148:30 GET and 192:30 GET P23 sequences of Figure 4.2.4-2. The 148:30 GET measurement sequence was the first (maximum range) measurement made during the transearth return after leaving the lunar sphere; the 192:30 GET sequence was the last navigation before reentry.

4.2.4.1 Options

Experience with P23 in initial APOLLO flights has dictated that certain options, originally considered nominal, be de-emphasized in favor of others or supplemented with alternative procedures.

The original P23 procedure specified manual maneuvers and optics pointing because the ISS was to have been powered down during cislunar coast to conserve power. Thus IMU-derived REFSMMAT information necessary for auto maneuver and optics would have been unavailable. The IMU is now left on, and automatic maneuver (R60) and optics pointing (R52) are therefore nominal procedure in P23 to minimize RCS fuel use.

4.2.4.1.1 Landmark Option.—The option to designate earth and lunar landmarks for marktaking by specifying the latitude, longitude, and altitude of each, though available in P23, is little used. The star-horizon measurement option has largely supplanted star-landmark sightings because adequate landmarks are not always available, and star image visibility is usually marginal against a bright earth image. (See the visibility criteria discussion in paragraph 4.2.4.3.)

4.2.4.1.2 Planet Option.—Another P23 option is the capability of selecting planets (e.g., Mars, Venus) for navigation by specifying the x, y, and z basic-reference components of their locations at a particular GET to the CMC via the DSKY. Unlike stars, whose inertial coordinates are fixed and may be stored in the CMC by star code, planet ephemerides are time-varying and must be obtained from tables for the desired measurement time.

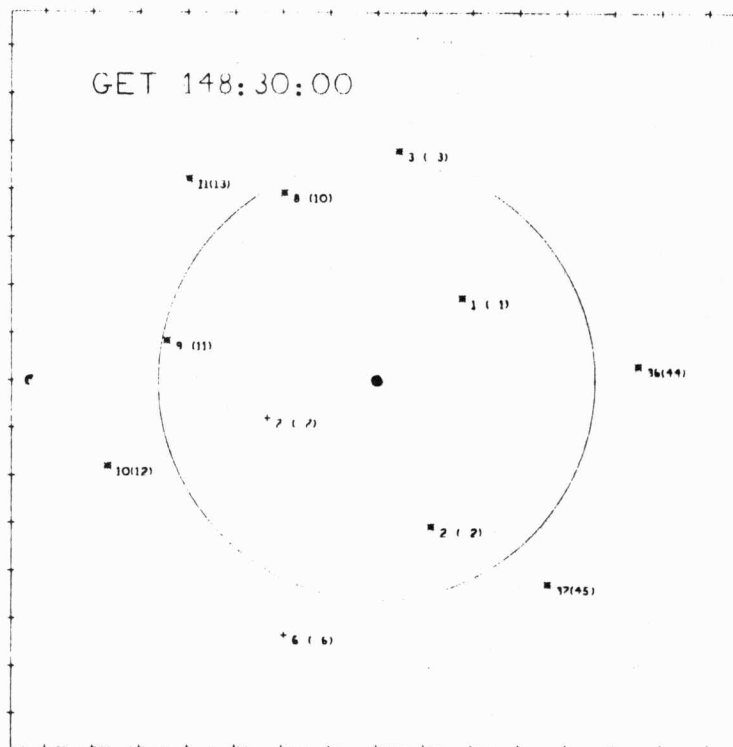


Figure 4.2.4-3a.

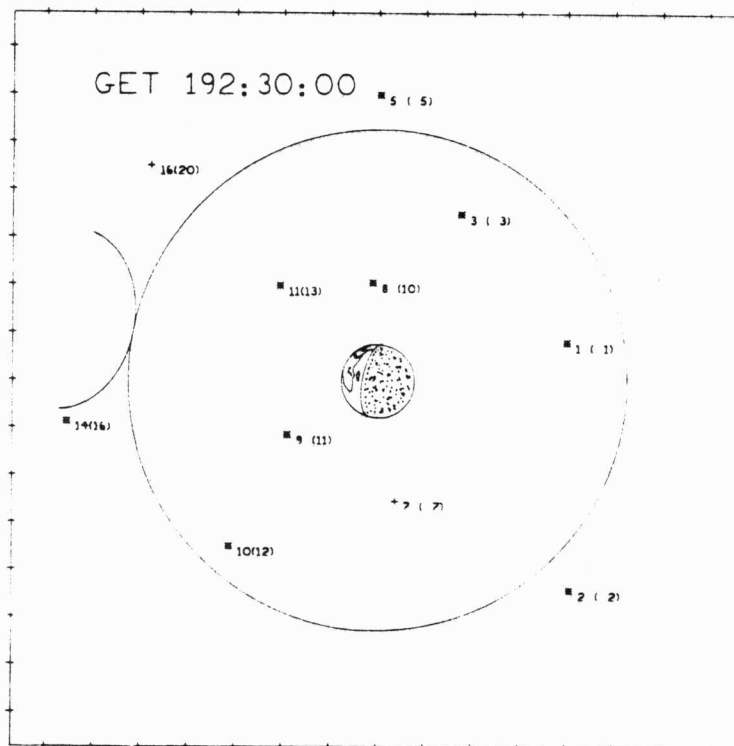


Figure 4.2.4-3b.

Figure 4.2.4-3. Available Measurement Stars Visible in SCT FOV at 148:30 GET and 192:30 GET during APOLLO 11

4.2.4.1.3 Landmark Calibration.—A differential visibility problem similar to the one mentioned under "Landmark Option" has caused the landmark calibration procedure to be de-emphasized in favor of star calibration.* Procedures for accomplishing minimum RCS maneuvers to point the LLOS at calibration stars have therefore been devised; calibration stars will henceforth be included in the measurement series. Optimum calibration stars can be pre-selected and identified in the checklist by star code. Factors that influence star selection and landmark visibility are discussed in paragraph 4.2.4.3.

4.2.4.1.4 Star Calibration.—P23 does not now facilitate maneuvers to calibration stars. Beginning with APOLLO 14, an option will be provided in P23 to automatically (via R60) point the SXT LLOS at a star for calibration (as distinguished from pointing it at the star's substellar point on the measurement planet, the only current option). The interim calibration procedure requires that P52 be entered before P23 to perform a minimum RCS-fuel maneuver to the attitude necessary to acquire the calibration star. P23 is then entered and R57, the calibration subroutine, is called to record the trunnion bias. If trunnion bias (VERB 06 NOUN 87) is normal, the astronaut keys VERB 94 ENTR in response to the VERB 06 NOUN 92 in R52, causing P23 to recycle to R60. R60 then maneuvers the spacecraft to the substellar point for the first measurement star, after which P23 measurement marktaking proceeds normally. Three-mark iterations of P23 follow for each of the remaining stars in the measurement sequence.

A number of other options exist, some internal to the program, others external. An example of the former is the VERB 94 ENTR option, which permits the program to be recycled if the vehicle or the optics are improperly aimed. Examples of external options are the routines and options (e.g., R30, R31, and NOUN 73) available to assist in evaluating the effects of navigation marks on the state vector and the trajectories that result. Refer to paragraph 4.2.2 for an explanation of the NOUN 73 option in P21 and to paragraph 4.2.4.5 for a discussion of post-measurement evaluation.

4.2.4.2 Procedures

Nominal P23 operation assumes automatic maneuver and optics pointing. The IMU must, therefore, be up and aligned to compute vehicle and optics pointing vectors.

* Applies mainly to earth-landmark-navigation; high-contrast lunar landmarks are plentiful so that measurements and calibration should still be feasible for moon-oriented navigation.

Similarly, appropriate DAP parameters (vehicle mass, DAP deadband and rate) must be loaded via R03 to obtain correct tracking dynamics.

4.2.4.2.1 Calibration Procedure.—To obtain optimum results from P23, angle measurements that achieve the full 10-arc-sec precision inherent in the OSS design are necessary. Trunnion biases in the 10–30-arc-sec range are caused by thermal gradients produced by heat sources within the OSS and, less importantly, by differential heating due to incident solar radiation. One-half hour must elapse after optics turn-on to achieve thermal equilibrium before the OSS is calibrated and used to obtain star-sight navigation marks in P23. The optics are often left on, so this will usually not be a problem. Spacecraft attitude during calibration should be consistent with measurement orientation to prevent gross changes (daylight-to-dark or vice versa) in the spacecraft-OSS solar-thermal environment. A SXT trunnion bias calibration should be performed before each P23 sequence and at half-hour intervals during the course of the update.

Current calibration procedure involves superimposing a star image obtained via the SLOS on the image of the same star obtained via the LLOS. This procedure requires that the spacecraft first be maneuvered to acquire the calibration star in the SXT LLOS FOV. Image superimposition is then accomplished by switching the OPTICS ZERO switch to ZERO, which drives the trunnion CDUs to zero, thus aligning the SLOS with LLOS. The trunnion is then adjusted via the OHC until the images coincide and a mark is taken; this records the trunnion CDU angle necessary to superimpose the images and compensate for trunnion bias.

The P23 calibration procedure occurs in the two phases outlined below, which correspond to steps 1–5 and 6–10, respectively of Table 4.2.4-I:

- a. An abridged pass through P52 is performed to obtain the optics shaft and trunnion angles of the calibration star in R1 and R2. This display provides the basis for a pure roll maneuver to null R1 (i.e., until R1 equals 0 or 180 deg) followed by a pure pitch maneuver to null R2, thus expending the minimum, feasible RCS fuel to obtain the desired orientation.
- b. A partial pass through P23 obtains the calibration routine R57 in which trunnion bias is recorded. If the trunnion bias displayed in VERB 06 NOUN 87 is acceptable, a VERB 94 ENTR response to the trunnion angle display (VERB 06 NOUN 92) causes P23 to recycle and call R60 for an automatic maneuver to the substellar point of the first measurement

TABLE 4.2.4-I

P23 CALIBRATION PROCEDURE (SHEET 1 OF 3)

Step	DSKY Display	Register Contents	Remarks
1.	Key V37 E52E		Select P52 for P23 calibration (IMU is already realigned).
2.	FL V04 N06	R1 00001 R2 0000x R3 Blank	Program requests IMU orientation. Set R2 = 3 (REFSMMAT) and PRO.
3.	FL V50 N25	R1 00015 R2 Blank R3 Blank	Is CMC to select two alignment stars ? ENTR (No)
4.	FL V01 N70	R1 000xx R2 Blank R3 Blank	Request Response Display Celestial Body Code. Astronaut should load star code for calibration star, switch optics to CMC and PRO. Program calls R52 auto optics position routine. If star code is 01-45g and the trunnion angle is not excessive ($T > 90^{\circ}$ = 00404 alarm code, $T > 50^{\circ}$ = 00407 alarm code), SXT shaft and trunnion angles will be displayed.
5.	V06 N92 or FL V51	R1 xxx.xx deg R2 xx.xxx deg R3 Blank	Shaft angle to nearest 0.01 degree. Trunnion angle to nearest 0.001 degree. If OPTICS MODE switch has been switched to MANUAL in R52, R53 will be selected and flash V51 (Please mark). Keying V16 N92E will display shaft and trunnion angle. With optics at CMC, the procedure is to initiate a pure roll maneuver with the RHC (roll left if $R1 = 0 - 180^{\circ}$, roll right if $R1 = 180^{\circ} - 360^{\circ}$) until $R1 = 0$ or 180° . Then perform a pure pitch maneuver (up if $R1$ reads 0, down if $R1 = 180^{\circ}$) until $R2 = 0$.

TABLE 4.2.4-I

P23 CALIBRATION PROCEDURE (SHEET 2 OF 3)

Step	DSKY Display	Register Contents	Remarks
6.	V37 E23E FL V05 N70	R1 000DE Star ID R2 00C00 LMK ID R3 00CD0 HOR ID	<p>Enter P23 for calibration. Re-quest measurement identification</p> <p>R1 = 000xx where xx is star code of measurement star.</p> <p>R2 = 00C00 where C = 1 for earth landmark, C = 2 for moon landmark.</p> <p>R2 = 00000 for horizon measurement.</p> <p>R3 = 00CD0 where C = 1 for earth horizon, C = 2 for moon horizon, D = 1 for near horizon, D = 2 for far horizon.</p> <p>R3 = 00000 for landmark measurement</p> <p>On calibration pass, load R2 = 0, R1 with star code of first measurement star (not calibration star) and R3 with appropriate code for earth or moon near or far horizon and PRO.</p>
7.	FL V50 N25	R1 = 202 R2 = Blank R3 = Blank	Do I want GNCS auto maneuver to star ID via R60 ? No, Key ENTR.
8.	FL V59		<p>R57 please mark; to calibrate:</p> <ol style="list-style-type: none"> 1. Set OPTICS ZERO switch to ZERO. 2. Slave SCT to SXT. 3. Perform MIC minimum impulse maneuver to center star in SCT FOV. 4. Set OPTICS ZERO switch to OFF. 5. Set OPTICS MODE switch to MAN. 6. Superimpose SLOS and LLOS images using OHC. 7. Mark.

TABLE 4.2.4-I

P23 CALIBRATION PROCEDURE (SHEET 3 OF 3)

Step	DSKY Display	Register Contents	Remarks
9.	FL V06 N87	R1 Blank R2 xx.xxx deg R3 Blank	R2 contains trunnion bias to nearest 0.001 degrees. Trunnion CDU granularity $\approx 0.003^\circ = 10$ arc-seconds. Max trunnion bias $0.010^\circ - 0.015^\circ$, typically. RECAL if excessive. Make at least 3 calibration marks to ensure marking consistency. A consistency of ± 1 bit (.003 deg) should be obtainable. Incorporate the last mark if it meets the above criterion; if not, make another mark and repeat until consistency is achieved. Set OPTICS MODE switch to CMC if acceptable and PRO to incorporate.
	NOTE:	Bias value may be loaded directly using V22N94E instead of repeating measurement.	
10.	V06 N92 FL V51 or FL V05 N 09 00404 in Rn ($T > 90^\circ$) or PROG alarm; key V05N09 to verify 00407 ($T > 50^\circ$)	R1 xxx.xx deg R2 xx.xxx deg R3 Blank	FL V51 will appear if OPTICS MODE is not in CMC position. Key V94E when V06 N92 flashes causing P23 to recycle. End of calibration, recycle to perform first star-horizon marks. Go to Table 4.2.4-II, step 6 (R60) after V94E recycle. Shaft and trunnion values displayed in R1 and R2 are angles between calibration star and measurement substellar point. If $T > 50^\circ$, maneuver manually to reduce before recycle.

star, after which P23 proceeds normally; that is, being entered again for each mark, unless another calibration maneuver is necessary, one-half hour later.

Table 4.2.4-I lists the displays in the P23 calibration procedure in the order in which they occur. The premaneuver P52 procedures require little comment beyond the remarks in the table. If the 50-deg 00407 trunnion angle alarm occurs, a minimum impulse maneuver using the RHC can be used to bring the SXT LLOS closer to the calibration star, or P52 can be terminated via VERB 34 ENTR at any flashing display. A 90-deg 00404 alarm should not occur unless a gross error is made in nulling PTC rotation.* Using the shaft and trunnion angle VERB 06 NOUN 92 displays, the astronaut can perform the pure roll and pure pitch maneuver procedure in the table to align the SXT LLOS on the calibration star, after which calibration can be performed.

After P23 is entered, the information loaded at the measurement ID display relates not to the calibration pass currently underway, but to the measurement star that will be marked on during the measurement made when P23 is recycled following calibration. R1 must contain the code of the first measurement star; R2 must equal all zeros, and R3 must be loaded with the appropriate planet and horizon codes.

After a PRO response at the VERB 50 NOUN 25 (R1 equals 00202) display, P23 will select R60. The astronaut may allow an automatic maneuver if the gimbal angles are acceptable. The astronaut must monitor the FDAI ball gimbal angle display to prevent gimbal lock. After R60 has driven to the substellar point, transfer of control to R52 is made by keying ENTR. R60 drives directly to the substellar point without regard to the measurement plane.

It is desirable to have the spacecraft aligned such that the spacecraft Y-axis is normal to the plane defined by the star-planet-spacecraft plane (i.e., parallel to the substellar horizon). This alignment will allow adjustment of the substellar point (making it parallel to the M-lines) by pure spacecraft roll. If the LM is attached, LM occultation will be prevented if the preceding condition is met along with the additional constraint of placing heads toward the planet (with a resultant shaft angle of 180 deg).

*

At the standard 0.03-deg Barbecue Mode rate, the spacecraft angular momentum will be nulled within 5 or 10 deg of the orientation at RCS firing.

If the trunnion angle is within limits (no VERB 05 NOUN 09 alarms), the optics shaft and trunnion angles of the measurement star will be displayed, and R52 will drive optics to acquire it in the SLOS. A switch to manual optics will then permit the optics to be maneuvered to register the star image on the horizon substellar point and to take marks in response to the flashing VERB 51.

After each mark is taken and confirmed, P23 will compute and display Δr and Δv changes which will be made in the state vector—if the mark is incorporated. The nominal incorporation criterion is that Δr and Δv not exceed 50 n. mi., 50 fps, respectively. Keying a PRO will incorporate the mark; keying a VERB 32 ENTR will reject it. Keying a 23 ENTR response to the VERB 37 that flashes after the mark is accepted, followed by the PRO, ENTR and PRO responses to the measurement ID, auto maneuver, and calibration displays, respectively, will obtain the flashing VERB 51 which requests the next mark on the same star.

4.2.4.2.2 Measurement Procedure.—If the IMU has not been aligned, P23 goes directly to the calibration routine, R57 (see Figure 4.2.4-4), and the astronaut must set the Optics Mode switch to MAN and manually maneuver the spacecraft to a calibration star. (See Figure 4.2.4-5.)

The computation of desired gimbal angles makes use of the VECPOINT routine which effectively rotates the LLOS into the substellar LOS vector (without constraining the rotation about the LLOS). This allows the astronaut to rotate the spacecraft and have the desired gimbal angle recomputed as often as desired by proper switch selection and response to the VERB 50 NOUN 18 display. (See step 6 of Table 4.2.4-II.) Unless the next substellar point is within the DAP deadband, the PRO response to select an auto maneuver is nominal. Subsequent procedures are similar to the nominal measurement performed after calibration described above and detailed in Table 4.2.4-II.

In the nominal procedure, the astronaut loads star-horizon data during the first flashing VERB 05 NOUN 70 display; flashing VERB 50 NOUN 25 (R1 equals 00202) appears next for the auto maneuver (R60) decision. (Refer to Table 4.2.4-II.)

The VERB 06 NOUN 89 landmark latitude-longitude-attitude display appears only if the unstored known landmark option is loaded in the target ID display.

The VERB 06 NOUN 88 display permits a planet to be identified by specifying its unit vector. The 37 stars in the star table have the x, y, and z components of their respective unit vectors permanently stored in the CMC according to star code.

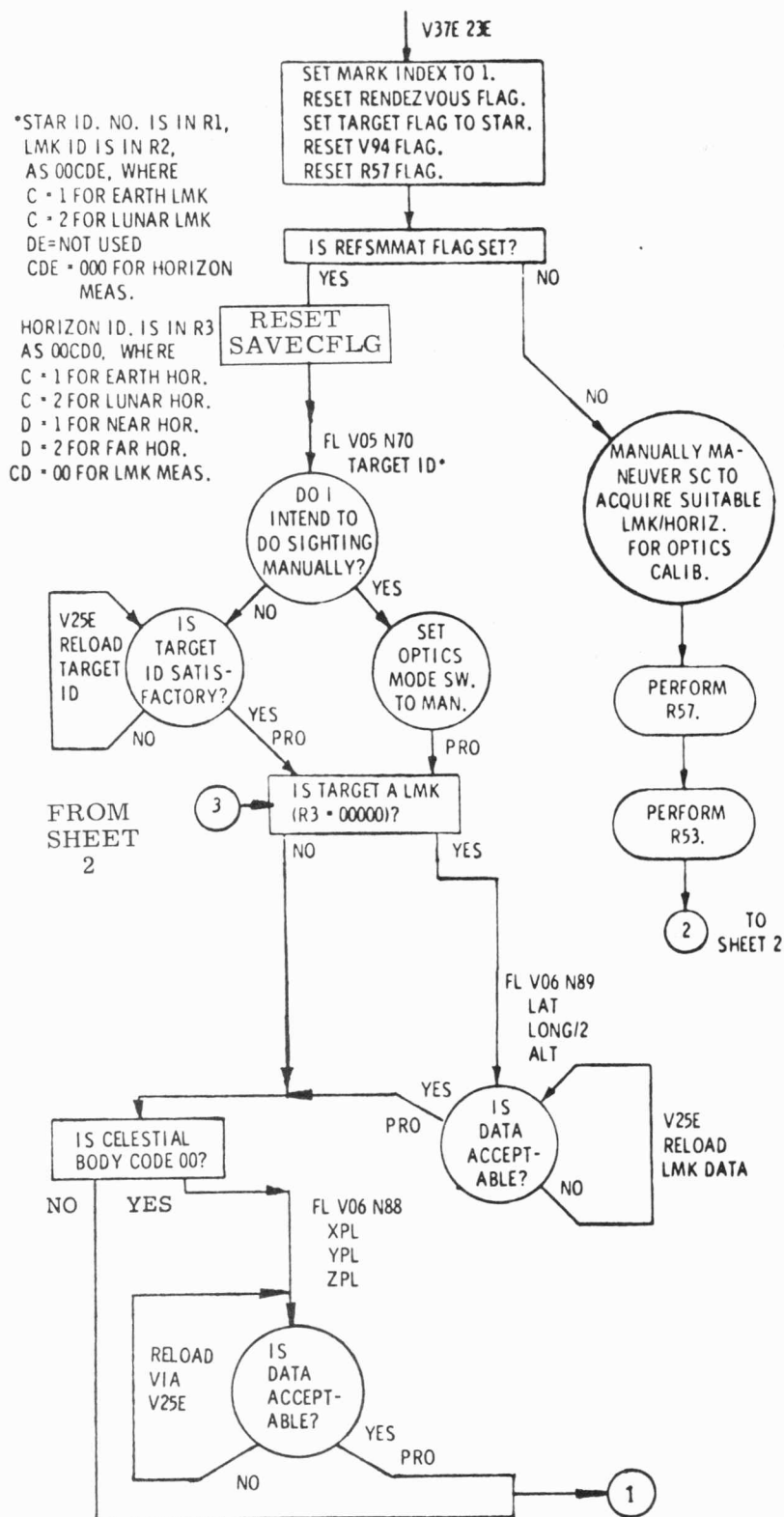


Figure 4.2.4-4. Cislunar Navigation Program (P23) (Sheet 1 of 3)

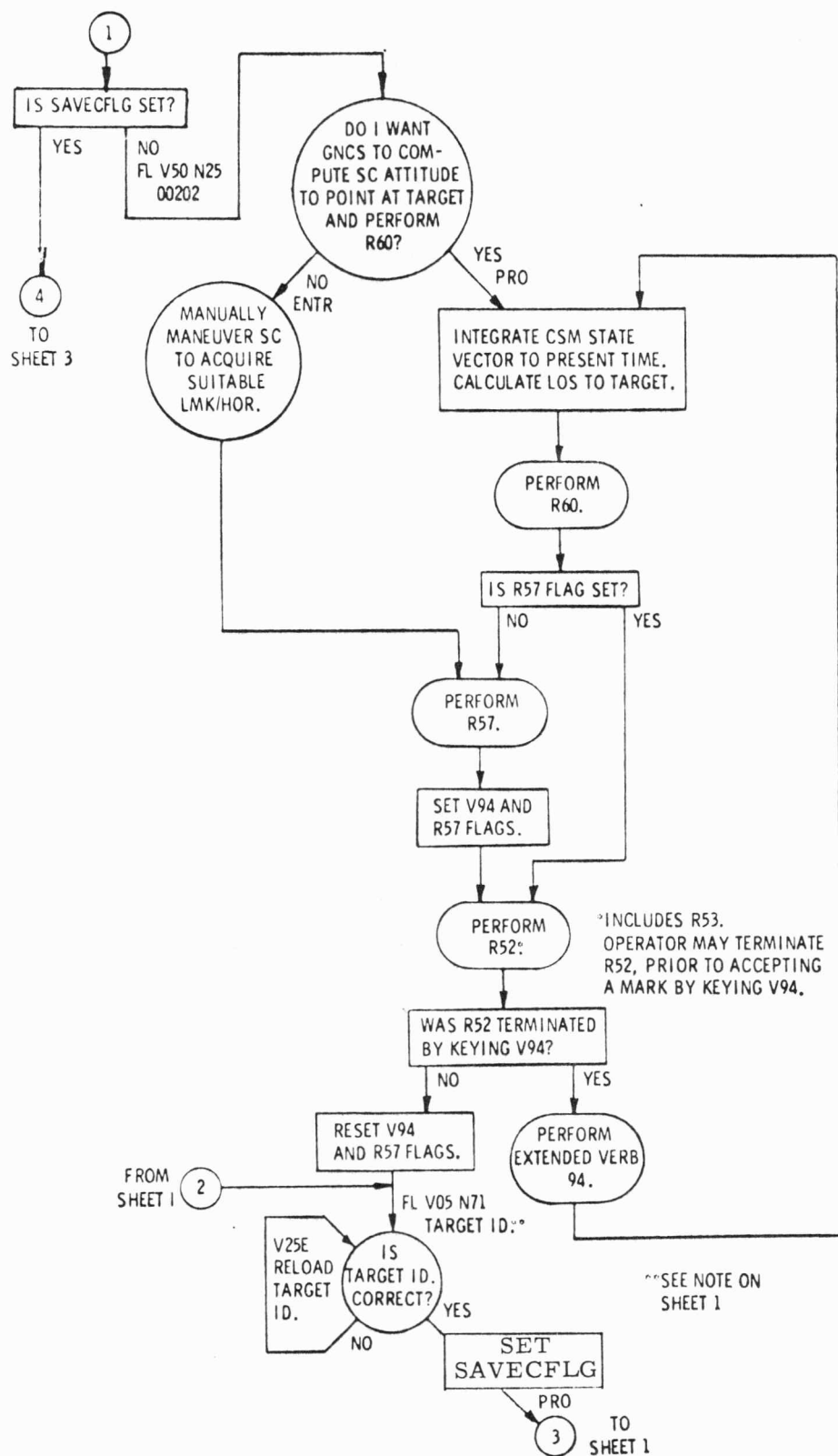


Figure 4. 2. 4-4. Cislunar Navigation Program (P23) (Sheet 2 of 3)

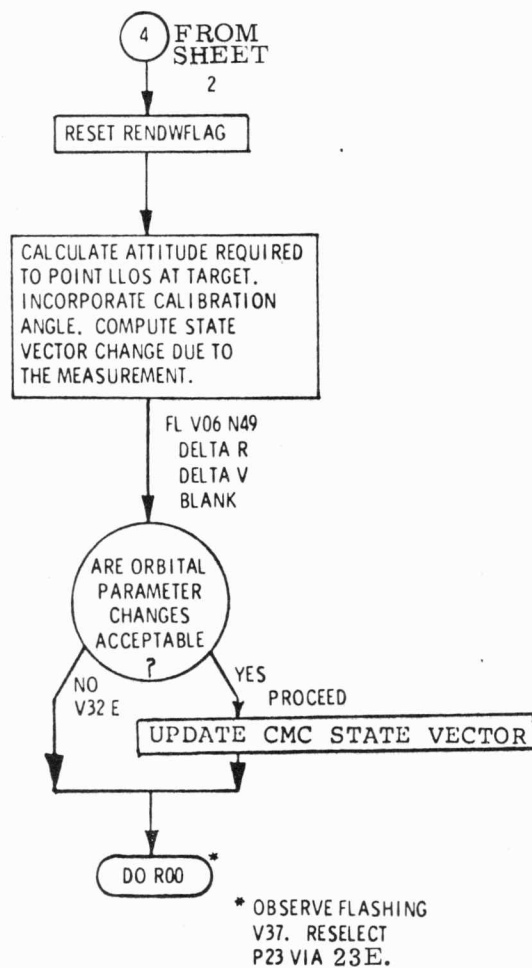


Figure 4.2.4-4. Cislunar Navigation Program (P23) (Sheet 3 of 3)

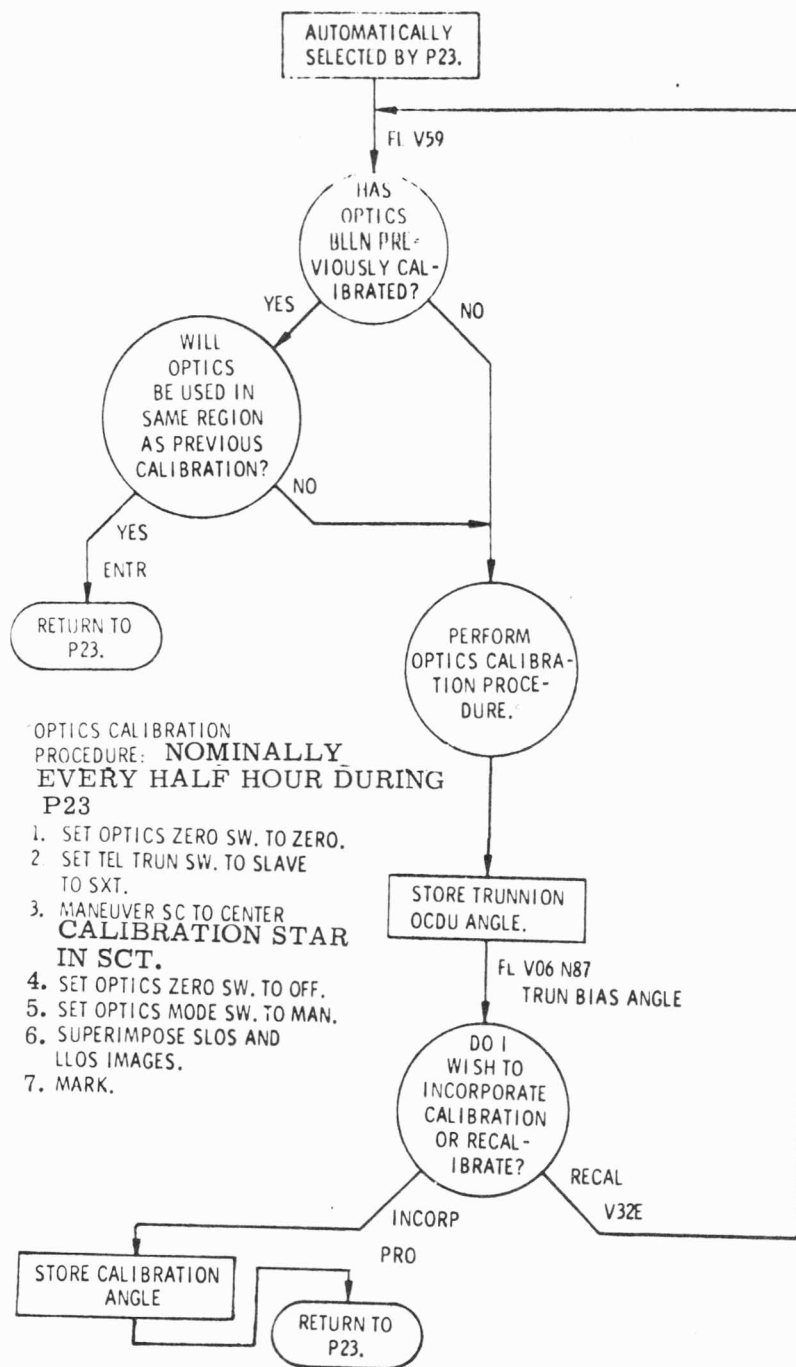


Figure 4.2.4-5. Optics Calibration Routine (R57)

TABLE 4.2.4-II

P23 DSKY INPUT OUTPUT ACTIVITY (SHEET 1 OF 4)

Step	DSKY Display	Register Contents	Remarks
1.	V37 E23E		Astronaut keys P23 major mode.
2.	FL V05 N70	R1 000xx R2 00C00 R3 00CD0	Star ID 00-45 ₈ Landmark ID C = 1 for earth landmark C = 2 for moon landmark R2=00000 for horizon measurement Horizon ID C = 1 for earth horizon C = 2 for moon horizon D = 1 for near horizon D = 2 for far horizon R3 = 00000 for landmark measurement PRO if correct. V25E to load
3.	FL V06 N89	R1 xx.xxx R2 xx.xxx R3 xxx.xx	Appears when R3 = 00000 in previous display. R1 = Latitude of landmark in degrees to nearest 0.001 degree. (+ = North). R2 = Longitude of landmark divided by 2 in degrees to nearest 0.001 degree (+ = East). R3 = Altitude of landmark in n. mi. to nearest 0.01 n. mi. above Fisher Ellipsoid (earth) mean lunar radius (moon)
4.	FL V06 N88	R1 .xxxxxx R2 .xxxxxx R3 .xxxxxx	Appears when R1 = 00000 in N70 of step 2. R1 = XPL X component of the unit position vector of the planet/star at GET. R2 = YPL Y component, same as XPL. ZPL Z component, same as XPL. All three in basic reference coordinates as 5-digit decimal fractions.

TABLE 4.2.4-II

P23 DSKY INPUT OUTPUT ACTIVITY (SHEET 2 OF 4)

Step	DSKY Display	Register Contents	Remarks
5.	FL V50 N25	R1 00202 R2 BLANK R3 BLANK	Requests astronaut decisions: auto maneuver to target LOS via R60 prior to calibration ? Or manual maneuver to calibration attitude ? PRO response selects auto maneuver, ENTR requires manual maneuver prior to performance of R57.
6.	FL V50 N18	R1 xxx.xx OGA R2 xxx.xx IGA R3 xxx.xx MGA	First display in R60. Display gimbal angles for desired maneuver to substellar point for measurement star. During AUTO maneuver, monitor FDAI for possible impending gimbal lock. If necessary, assume manual control via RHC. After a manual take-over, the astronaut can have the resulting gimbal angles displayed by returning to CMC-AUTO and keying PRO. A PRO response always results in a VECPOINT computation of desired gimbal angles followed by a check to determine if an AUTO maneuver is allowed (SC CONT SW = CMC and MODE SW in AUTO). If allowed, the CMC displays V06 N18 and initiates the maneuver; if not allowed, the CMC redispays V50 N18. ENTR will call R57.
7.	V06 N18	R1 xxx.xx OGA R2 xxx.xx IGA R3 xxx.xx MGA	Final gimbal angles will be displayed nonflashing during maneuver. V50 N18 resumes flashing when maneuver is complete (substellar point is within DAP deadband) or interrupted by astronaut.

TABLE 4.2.4-II

P23 DSKY INPUT OUTPUT ACTIVITY (SHEET 3 OF 4)

Step	DSKY Display	Register Contents	Remarks
8.	FL V59 FL V06 N87		Calibration Mark Request R57. Does maneuver calibration optics history indicate calibration required ? If so, mark, otherwise go to step 9 (R52) via ENTR or PRO. If trunnion bias angle resulting from calibration differs from previous value by more than 10-arc-seconds, incorporate (PRO) or recalibrate via (RECAL) and compare second biases prior to incorporation.
9.	V06 N92	R1 xxx.xx R2 xx.xxx R3 Blank	R52 auto optics shaft and trunnion angles. If trunnion $<50^{\circ}$ (no 404 or 407 PROG alarm) and OSS is in CMC mode, optics CDUs will drive until SLOS optics achieve star-horizon superimposition. Recycle via V94E returns to step 6.
10.	FL V51		R53 sighting mark routine selected by setting OPTICS MODE SW to MAN. When star appears in SXT FOV, astronaut must maneuver SC with RHC so that star image is aligned with earth/moon horizon at substellar point. FL V51 Please Mark Request is terminated by pressing optics MARK button. Astronaut may accept or reject each mark. MARK REJECT erases stored CDU angles of last mark and decrements mark counter. V94E prior to ACCEPT or REJECT returns to step 6.

TABLE 4.2.4-II

P23 DSKY INPUT OUTPUT ACTIVITY (SHEET 4 OF 4)

Step	DSKY Display	Register Contents	Remarks
11.	FL V50 N25	R1 00016 R2 Blank R3 Blank	Appears after MARK is taken. MARK REJECT will erase mark and return to step 10. FL V50 N25 Terminate Mark Sequence display will appear. PRO response will terminate R53 and return to P23.
12.	FL V05 N71	R1 000xx R2 00C00 R3 00CD0	Confirm measurement ID. Must conform to Star, Landmark and Horizon codes displayed in step 2. R1 = 00 if planet was used, 01 to 45 (octal) if one of 37 coded stars. If ID is correct (V05 N70), PRO.
13.	FL V06 N89	R1 xx.xxx R2 xx.xxx R3 xxx.xx	Appears when R3 = 00000 in previous display. R1 = Latitude of landmark in degrees to nearest 0.001 degree. (+ = North). R2 = Longitude of landmark divided by 2 in degrees to nearest 0.001 degree (+ = East). R3 = Altitude of landmark in n. mi. to nearest 0.01 n. mi. above Fisher Ellipsoid (earth) mean lunar radius (moon)
14.	FL V06 N88	R1 .xxxxxx R2 .xxxxxx R3 .xxxxxx	Appears when R1 = 00000 in N70 of step 2. R1 = XPL X component of the unit position vector of the planet/star at GET. R2 = YPL Y component, same as XPL. ZPL Z component, same as XPL. All three in basic reference coordinates as 5-digit decimal fractions.
15	FL V06 N49	R1 xxxx.x R2 xxxx.x R3 Blank	Display orbital parameter changes R1 = ΔR , position change due to last mark in n. mi. to nearest 0.1 n. mi. R2 = Δv , velocity change due to last mark in fps to nearest 0.1 fps. PRO will cause mark to be incorporated, updating CMC state vector. V32E will cause recycle. Incorporation criterion is: $\Delta R < 50$ n. mi. and $\Delta v < 50$ fps.
16	FL V37xx		In either case, V37 will flash. P23 can be reselected by 23E response if necessary. PRO, ENTR and PRO responses at steps 2, 5 and 8 will return flashing VERB 51 (step 10) for next mark on same star.

The unit vectors of planets (which are time-varying) may be precalculated and written into the checklist for use in particular mission situations. Tables are provided that give the unit vectors of the planets on which measurements might be made as a function of GET. The VERB 06 NOUN 88 display following a 00 star code is provided to permit celestial bodies other than the ones identified by prestored star codes to be marked.

After the automatic-maneuver (R60) and optics-positioning routines (R52) have caused the optics to acquire the measurement star and its associated substellar horizon, it is possible for the astronaut to use the SCT to verify from star charts of nearby celestial bodies that the star in the SXT FOV is indeed the one desired. If the ΔR , Δv display is greater than expected, the astronaut should consider rejecting the update and repeating the measurement with special concern for the input data (e.g., near versus far horizon and star ID) and a careful review of the star background. If all checks confirm a proper measurement, the ΔR , Δv should be accepted.

4.2.4.3 OSS Performance and Visibility Criteria

Near the earth, earth light scattered in the optics tends to obscure stars in its vicinity. This may reduce the population of stars available for navigation angle measurements to three or four situated more than 30 deg from the earth horizon LOS; i.e., in the outer periphery of the 100-deg cone covered by the SXT trunnion. Because the earth's image is much brighter than that of a star, the optics LLOS was designed to transmit only 3.2 percent of incident light and the SLOS to transmit about 25 percent to ensure appropriate differential visibility for star-horizon superimposition. Because of the 25-fold incident light attenuation through the LLOS and the fact that earthshine tends to swamp star images near the earth, calibration may require maneuvers to attitudes that point the LLOS 20 or 30 deg from the earth. At the 0.2-deg/sec DAP rate, calibration maneuvers may require several minutes. Thus a trade must be made between frequent calibration (which ensures low-measurement bias and precise navigation), time, and RCS fuel consumption.

4.2.4.4 Influence of Measurement Geometry on State Vector

Figures 4.2.4-1a and b show the locus of spacecraft position determined by a single star-horizon measurement to be a cone of revolution about the horizon line of sight, with its apex angle (2θ) twice the angle formed by the star LOS and the horizon LOS. The onboard measurement technique used is not deterministic as the illustration tends to imply, but employs a statistical-filtering technique to produce an optimum linear combination of weighted increments from each angle measurement. Each

star-horizon angle measurement provides position information primarily in the plane of the measurement and orthogonal to the horizon LOS. A geometry vector b (Figures 4.2.4-1a and b) associated with each star-angle measurement characterizes its information content. The statistical uncertainty of vehicle position is reduced primarily along a dimension parallel to the b vector for each measurement star. Therefore, angle measurements should be made on stars located in different measurement planes. However, stars with a large b vector component in the orbital plane are preferred.

A sequence of P23 angle measurements processed through the W-matrix to produce statistically optimum weighted updates to the onboard state vector differs fundamentally from a simultaneous 3-dimensional fix on three well-separated (ideally orthogonal) stars. P23-derived position information efficiently minimizes state-vector uncertainties in a plane orthogonal to the horizon LOS, but is somewhat less effective in reducing R and \dot{R} uncertainty along the LOS. The dominant consideration in providing position and velocity inputs to P37 is minimizing uncertainty in the radial miss-distance in the orbital plane of the ± 20 n. mi. reentry window. The effect of this on P23 procedure is to dictate that, whenever possible, star measurements be made on stars whose measurement planes are near the orbital plane.

Notice that in the two sets of measurement stars in Figures 4.2.4-3a and b (corresponding to No. 9 at 148:30 and No. 11 at 192:30 in Figure 4.2.4-2), the last star marked on is nearest the (horizontal) orbital plane, consistent with the above discussion. This principle should be borne in mind if deviations from prescribed measurement schedules are necessary.

Note that the measurement schedule for each sequence of P23 activity on the mission flight plan is designed to minimize RCS fuel consumed by vehicle maneuvers necessary to orient the LLOS toward the substellar points of the successive measurement stars in each sequence. Any unscheduled P23 activity should also be carefully planned to minimize RCS maneuvers.

4.2.4.5 Post-Measurement Evaluation

Figure 4.2.4-6 shows the change in perigee that resulted from a group of 15 sightings made on the lunar horizon at a distance of 45,000 n. mi. during the translunar leg of APOLLO 8. At the end of this group of measurements, the indicated perilune was 67.1 n. mi., about 1.8 n. mi. less than the value later reconstructed from MSFN groundtrack data. Perigees computed onboard using either P37 or R30 (obtainable

4.2.4-24

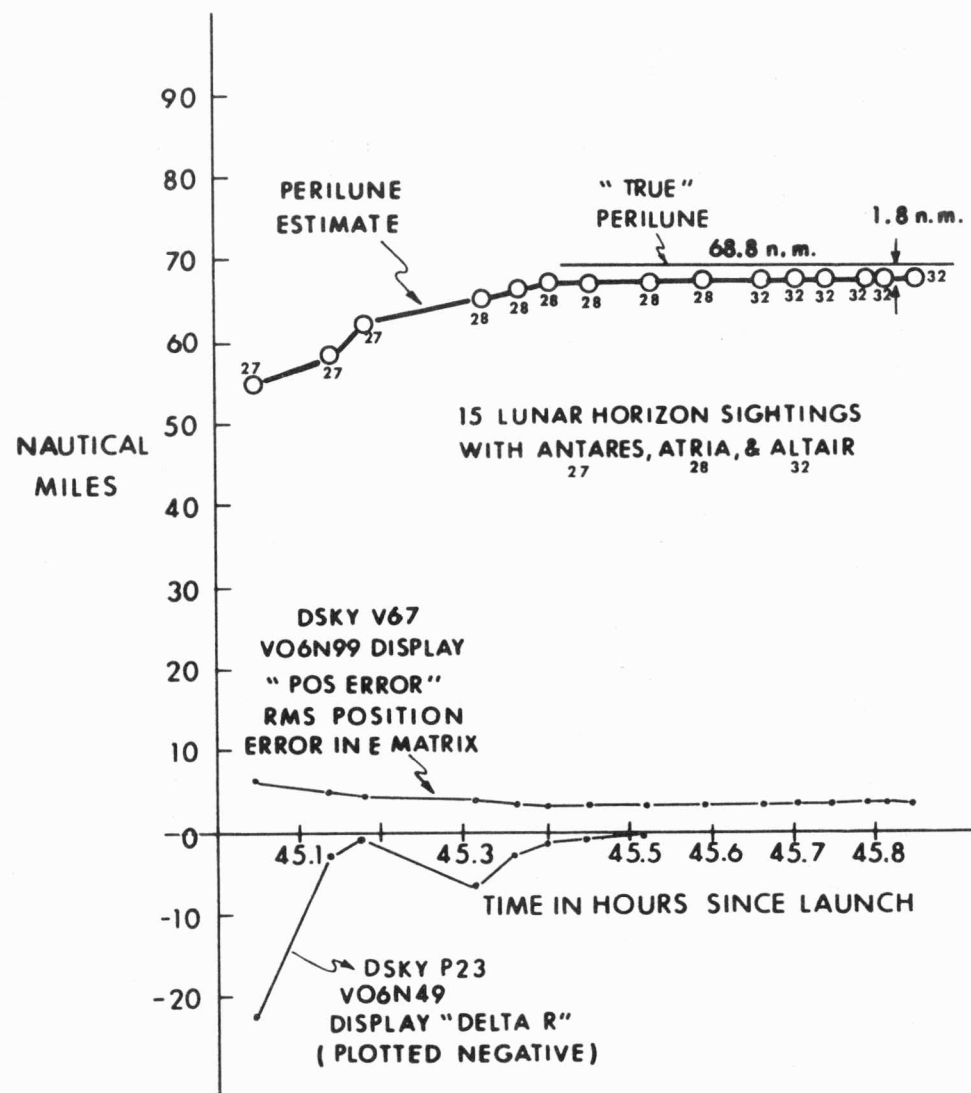


Figure 4.2.4-6. APOLLO 8 Translunar Midcourse Navigation

with VERB 82) should converge in the manner shown during a sequence of P23 star-horizon measurements, whether earth- or moon-centered.

4.2.4.6 Effects of Calibration and Substellar Errors

Frequent calibration is recommended to compensate for optical biases caused by thermal effects (both internal and external). An uncalibrated 20-arc-sec bias will cause a 20-km position error at a 100,000-mile range. Another potential source of error is bad marktaking technique, which results when the measurement star image is allowed to wander from the substellar point by more than 1 deg. The 1/2-deg DAP deadband limit will, at long ranges where the earth may subtend as little as 2 deg, bring the star image only within 15 or 20 deg of the substellar point. The astronaut must therefore ensure that the image is properly registered on the substellar point before marking.

At maximum range, the angle subtended by the earth's image is comparable to the SXT FOV so that the curvature of the earth gives a good visual cue as to whether a star image is at the substellar point or not. Nearer the earth, the DAP will achieve acceptable pointing accuracy but the reduced curvature of the terrestrial limb gives somewhat vague clues as to where the star image bisects the earth image. Consequently, there is a tendency to allow the star image to slide off to one side. The effect on angle measurement accuracy of an aiming error in substellar alignment increases as the square of the error: a 4-deg substellar alignment error produces an acceptable 2-arc-sec horizon error, but accuracy rapidly degrades beyond a few degrees.

4.2.4.7 Marking on the Horizon

Two factors must be considered in aligning the measurement plane. The first is determining the substellar point on the horizon. The cue for making this determination is the reticle pattern. The star image should be moved to the point on the horizon where a line tangent to that point is parallel to the horizontal axis of the reticle pattern. Figure 4.2.4-7 illustrates this alignment. The second is orienting the spacecraft so the star image and substellar point fall in the center two-thirds of the field of view. Judging the parallelism of the reticle to the tangent at the substellar point correctly is the most critical alignment operation. If the substellar point is found to lie near the side of the field of view, the spacecraft should be maneuvered to move this point near the center. The vertical location of the field of view is not critical.

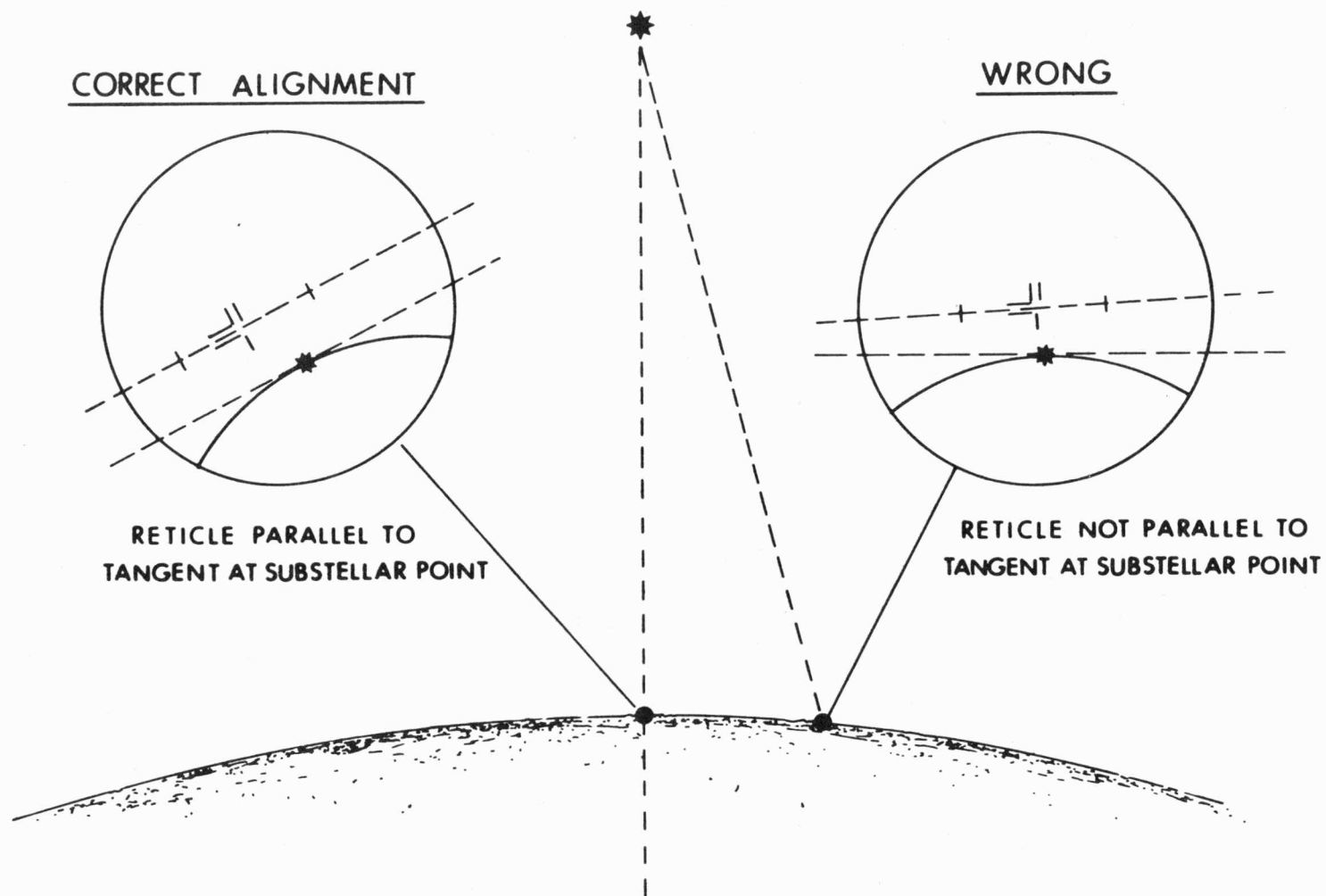


Figure 4.2.4-7. Correct Reticle Alignment with Substellar Tangent for Marktaking

To define the location of the earth's horizon, the center of the star image should be placed on the upper threshold of the atmosphere. The center, not the edge, of the star image should be used since focus and star magnitude affect the size of the image. The upper threshold of the earth's atmosphere does not appear as a sharp boundary.

Considerable variation exists in where different people perceive the threshold to be; each person, however, can accurately repeat his original selection. For this reason, APOLLO flight plans call for a series of marks to be made as close to the earth as possible to determine the horizon altitude that the navigator on each mission prefers to use.

4.2.4.8 Influence of W-Matrix on ΔR , Δv Mark Accept/Reject

Current policy is to reinitialize the W-matrix only once at the beginning of P23 takeover to a large diagonal value provided in a contingency table. (See Table 4.2.4-III.) The large W-matrix initialization for the first transearth navigation measurements (30,000 feet and 30 fps) is to allow for the possibility of errors in the TEI burn. The large W-matrix does not adversely affect nominal performance, but it will cause a state vector with large errors to converge where a small one might not. The W-matrix is only initialized once during the transearth return. P23 is not used during transearth coast unless communications are lost prior to entry-minus-30 hours. Table 4.2.4-III gives W-initialization values for the G-mission. The growth of the W-matrix with extrapolation over the intervals between measurements is expected to provide adequate gain for subsequent P23 measurements. Since the size of the W increases exponentially with time, the size of the first ΔR , Δv in a sequence of P23 measurements will vary predictably with time. A good check on W growth prior to P23 measurement activity can be had using the W-matrix position component display, VERB 67 ENTR. Knowing the size of the W to be nominal before marktaking ensures that marks taken will in fact have the desired effect on the state vector.

The prime criterion for accepting or rejecting ΔR and Δv updates to the state vector is a fairly crude 50-n. mi./50-fps GO/NO-GO test. If ΔR or Δv is greater than 50, reject the update and repeat the mark, making sure it is accurate and on the correct star. If the second ΔR , Δv is close to the first, accept it unless it is truly excessive—in which case consider recalibrating. If very large values persist, the SXT may be broken; try the SCT.

TABLE 4.2.4-III
RECOMMENDED PROCEDURE IN CASE OF COMMUNICATION LOSS

Communication Loss Time (hr from TEI)	W-Matrix To Be Input at 1st Mark	Batches of Data To Be Taken
0 - 1.5	30,000/30	All
1.5 - 10	73,000/5.0	2nd through end of schedule
10 - 35	30,000/0.5	1st beginning after loss through end of schedule
35 - Entry*	None	None

* This assumes a MSFN update at TEI +35 hours.

The only guarantees of state vector quality using P23 are an adequate W-matrix, a plausible $\Delta R, \Delta v$ for the first mark, and convergent $\Delta R, \Delta v$ over a P23 sequence. The best guarantee of success is to adhere to the flight plan and utilize the contingency procedures in the checklist.

4.2.4.9 Alarms

A list of alarms that may be encountered in P23 and a brief explanation of each follows:

- a. Alarm code 00120 is displayed if the optics are not zeroed.
- b. Alarm code 0016 is displayed if the optics are taken out of zero before 15 seconds has elapsed.
- c. Alarm code 00115 is displayed if an optics torque request is made and the mode switch is not at CMC.
- d. Alarm code 00404 is displayed if the trunnion angle exceeds 90 deg.
- e. Alarm code 00407 is displayed if the trunnion angle exceeds 50 deg.

5.2.1 P30, External Δv -CMC

The purpose of P30 is to enable an external Δv maneuver to be targeted in local vertical coordinates, to initialize certain registers for P40/P41, and to display parameters related to an external Δv maneuver. The program can be used either with an uplinked t_{IG} and velocity change vector, to accomplish a plane-change maneuver calculated in R36, or with input in local vertical coordinates from any other source. Figure 5.2.1-1 is a flowchart of P30.

5.2.1.1 P30 Assumptions

The assumptions under which P30 operates and a brief explanation of each follow:

1. The above-mentioned t_{IG} and velocity-change vector have been uplinked via P27, were computed in R36 and recorded by the astronaut as T(EVENT) and (0, $-\dot{Y}$, 0) (assuming the CM was chosen as the vehicle) or a maneuver has been input from some other source.
2. If this is an uplinked burn, then concurrent with the operation of P27, a PAD has been voiced up from the ground.
3. The ISS need not be running or aligned for P30 to run to completion.
4. If P30 is run during rendezvous, Rendezvous Navigation (P20) can continue to run and marks can be incorporated during the first two flashing displays.
5. If the burn is ground-targeted, P30 is keyed in with sufficient time to allow for ground confirmation of displayed burn parameters.

5.2.1.2 Discussion of Inputs and Outputs

Tables 5.2.1-I and 5.2.1-II delineate P30 inputs and outputs, respectively. Noteworthy explanations of these inputs and outputs are given below.

If the maneuver is uplinked and any of the inputs or outputs are out of tolerance with the PAD voiced up from the ground, either the ground computer or the CMC has a bad state vector, or is malfunctioning. The burn should be postponed until new parameters can be uplinked, or the computer malfunction is diagnosed and corrected. If all outputs agree, within tolerances, with the PAD, or if the maneuver is on-board calculated to correct out-of-plane conditions, PRO should be used for inputs 1 and 2 and outputs 1, 2 and 3. Output 4, VHF and SXT marks, is a part of NOUN 45, the exit display for all targeting programs, and is relevant only if P30 is used during the rendezvous sequence. Output 5, time from ignition, is self-explanatory.

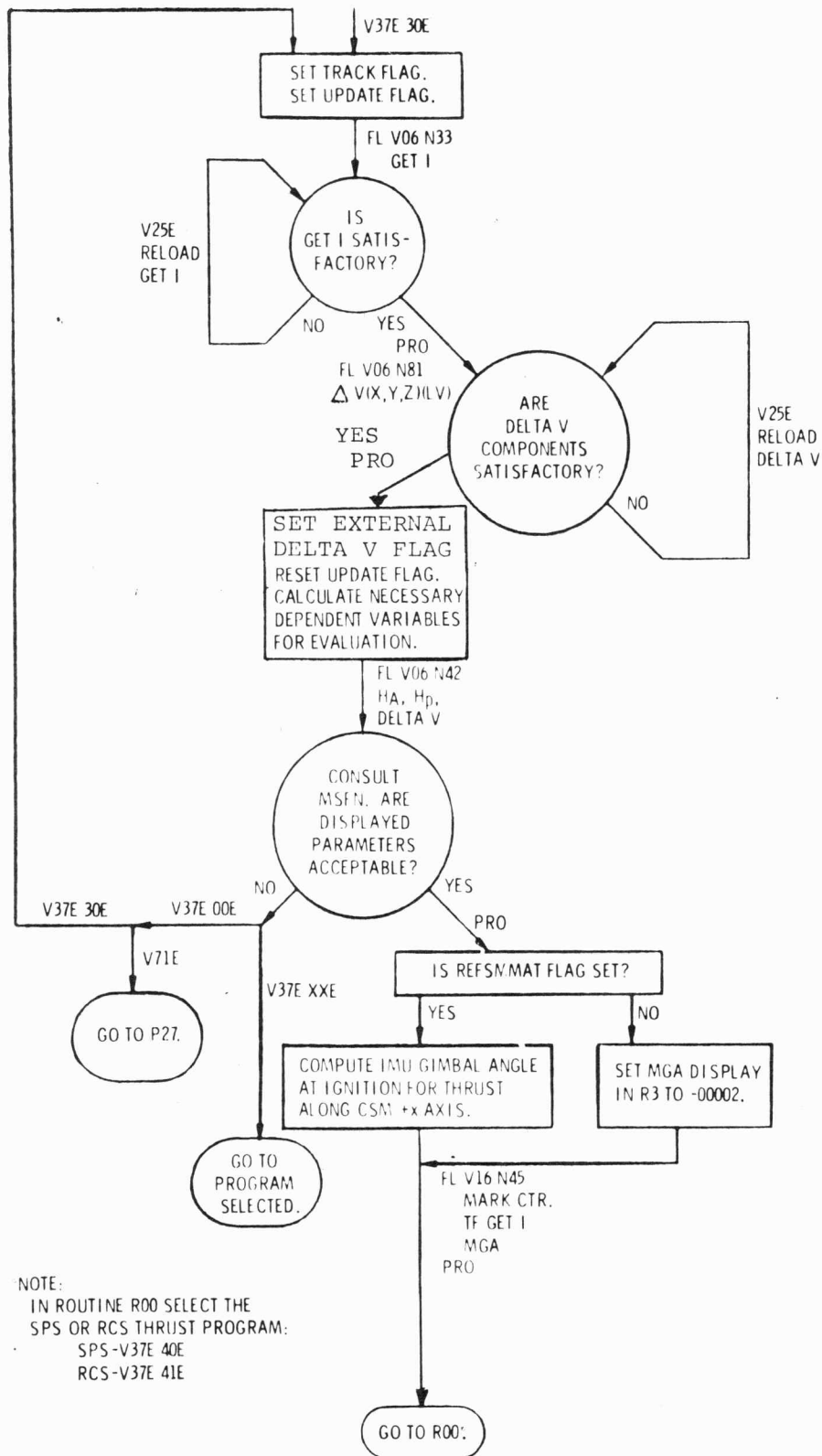


Figure 5.2.1-1. External Δv Program (P30)

TABLE 5.2.1-I
EXTERNAL Δv INPUTS (P30)

Input	Identification	Display Mnemonic	DSKY	Register	Comments
1.	Time of ignition	TIG	FL V06 N33	R1 oxxxx. hr R2 oooxx. min R3 oxx.xx sec	If the burn is uplinked, these registers will display the uplinked t_{IG} . If an onboard-calculated out-of-plane maneuver is being targeted then T(EVENT) must be loaded.
2.	Impulsive velocity change vector	DELTA V(LV)	FL V06 N81	R1 xxxx.x X R2 xxxx.x Y R3 xxxx.x Z	If the burn is uplinked, these registers will display the uplinked Δv (LV). If an onboard-calculated out-of-plane maneuver is being targeted, then (0, - \dot{Y} (CSM), 0) must be loaded.

TABLE 5. 2. 1-II
EXTERNAL Δy OUTPUTS (P30)

Output	Identification	Display Mnemonic	DSKY	Register	Comments
1.	Apogee altitude above pad radius/latest landing site radius	APO ALT	FL V06 N42	R1 xxxx.x n. mi.	Maximum number (9999.9), if scaling is exceeded.
2.	Perigee altitude above pad radius/latest landing site radius	PER ALT	FL V06 N42	R2 xxxx.x n. mi.	Maximum number (9999.9), if scaling is exceeded.
3.	Magnitude of velocity change	DELTA V	FL V06 N42	R3 xxxx.x fps	
4.	Rendezvous marks taken	MARK-COUNT	FL V16 N45	R1 xxBxx VHF marks taken, optics marks taken	
5.	Time from ignition	TFI	FL V16 N45	R2 xxBxx min, sec	Maximum reading, 59 min, 59 sec; negative before t_{IG} , positive after t_{IG} .
6.	Middle gimbal angle	MGA	FL V16 N45	R3 xxx.xx + degrees if alignment of IMU is known. -00002, otherwise.	

If R3 in NOUN 45 (output 6) indicates an excessive MGA (perhaps greater than 70 deg), the astronaut should consider realignment. If the ISS is not running, or if its alignment is unknown (in both instances, output 6 equals -00002), it must be powered up, and/or aligned before the burn. After the computer has received a PRO response to VERB 16 NOUN 45, P30 exits via R00 (flashing VERB 37).

Note that although P30 was once used for determining orbital parameters, especially for translunar and transearth coast, VERB 82 has now supplanted that function.

WARNING: The calculation of the apogee and perigee of the orbit resulting from the P30-targeted maneuver is based on an impulsive $\Delta \mathbf{v}$, and can be very wrong for maneuvers of long duration.

If either P40 or P41 is keyed in after a P30-targeted burn, and then P30 is again keyed in (for the same burn), input 2 DELTA V(LV) should be reloaded with the original value, since P40/P41 rotate this vector through a central angle and then store it back in the original location eliminating the unrotated vector.

5.2.2 P32, Coelliptic Sequence Initiation Targeting (CSI) —CMC

P32 is part of the coelliptic sequence (P32 plus P33) of rendezvous targeting. The coelliptic sequence is designed to result in orbits in which the difference in altitude between the two orbits is nearly constant. Once coelliptic orbits have been achieved, the transfer phase (P34 plus P35) follows. This phase is designed to effect an intercept trajectory and a braking maneuver, allowing docking by the pilot of the active vehicle. Maneuvers to correct out-of-plane conditions can be made at any time in the rendezvous sequence. (See Figure 5.2.2-1.)

Two thrusting maneuvers make up the coelliptic sequence, the CSI (coelliptic sequence initiation) maneuver and the CDH (constant delta height or altitude) maneuver. P32 computes a horizontal maneuver for CSI parallel to the plane of the passive vehicle at the astronaut-specified t_{IG} (CSI).

The magnitude and direction of this maneuver depend on four factors:

- a. The state vectors of the two vehicles at t_{IG} (CSI)
- b. The astronaut-specified time for the transfer phase initiation (TPI)*
- c. CDH apsidal crossing (or 180-degree option)
- d. The line-of-sight elevation angle (E).**

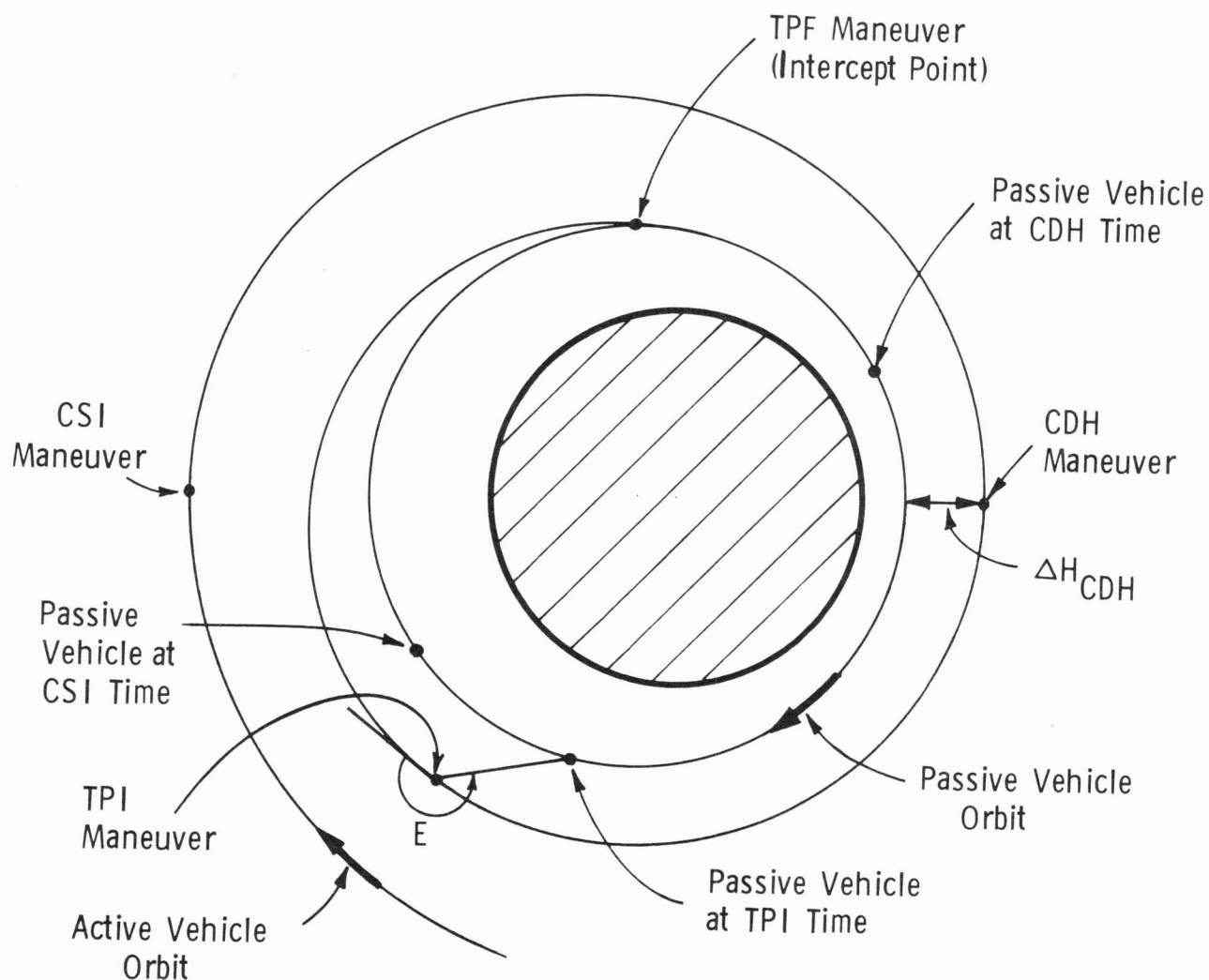
5.2.2.1 CSI Maneuver

In the nominal case, rendezvous is initially started with a poor estimate of the LM state vector; Rendezvous Navigation is therefore needed to improve the estimate of that state vector. Once that is done, the CSI maneuver must be targeted via P32, and then accomplished via P40 or P41.

AVERAGEG, which updates the state vector during powered flight, tends to degrade the estimate of that vector so that Rendezvous Navigation is again needed to improve the state vector. During rendezvous, the cycle repeats: navigation, targeting,

* t_{IG} (TPI) will usually occur at midpoint of darkness to allow good lighting conditions for final rendezvous.

** The line-of-sight elevation angle (E) allows the pilot of the active vehicle to boresight on the passive vehicle at t_{IG} (TPI). In this case, to boresight means that the thrust vector will be nearly coincident with the SXT LOS to the LM. As a back-up to computer failure, the astronaut may thrust while holding the CM in the SXT LOS attitude.



NOTE: ΔH_{CDH} is not strictly LM altitude minus CSM altitude, but the altitude of the point on the LM or orbit directly below the CSM at CDH, minus the CSM altitude. This distinction becomes significant when the passive vehicle is in a highly elliptical orbit and the central angle between the two vehicles at the CDH time is large. (This diagram is not in scale.)

Figure 5.2.2-1. An Example of a CSM-active Rendezvous Configuration

maneuver. Four targeting programs are used for coelliptic sequence rendezvous, and each must interface with P20 and P40 or P41.

P32 is designed to run while Rendezvous Navigation (P20) is operating. Preliminary estimates of the maneuver can be made before navigation is completed. P32 targets an external Δy maneuver for P40 or P41.

P32 contains an iteration loop, using the CSI Δy as the independent variable to obtain the specified TPI conditions. Under nominal flight configuration, the iteration scheme converges very quickly; the total final computation usually takes about 3 minutes.

As was mentioned above, rendezvous navigation can be carried on while P32 is running. Automatic VHF marks can accumulate throughout the program. SXT marks can be taken during any of the flashing displays of P32, until PRO is keyed in response to VERB 16 NOUN 45, by using R21 or R23. If marks are to be taken, the ISS must be operating and aligned. This is a requirement of P20.

P32 depends on a good knowledge of the state vectors of the two vehicles with respect to each other. Since P32 is performed after injection or abort, a situation that usually gives a poor initial estimate of the LM state vector, a certain minimum number of marks should be taken before final computation in P32. This number is mission-dependent, but usually fifteen optics and fifteen VHF marks will be sufficient.

5.2.2.2 Discussion of Inputs and Outputs

A user-oriented flowchart and two tables summarizing input and output of P32 follow. The information below is necessary to properly interpret the flowchart, Figure 5.2.2-2:

TRACK and UPDATE flags refer to P20. If TRACK flag is set, tracking is allowed; if it is reset, tracking is not allowed. If UPDATE flag is set, the state vector may be updated from marks; if reset, the state vector may not be updated from marks.

REFSMMAT FLAG SET means IMU alignment is known. If REFSMMAT flag is reset, IMU alignment is not known.

FINAL FLAG SET indicates the astronaut has keyed in PRO in response to VERB 16 NOUN 45. FINAL FLAG RESET indicates he has not.

Table 5.2.2-I lists the input displays of P32, which all come at the beginning of P32. Under nominal conditions, program inputs are as indicated on the voiced-up

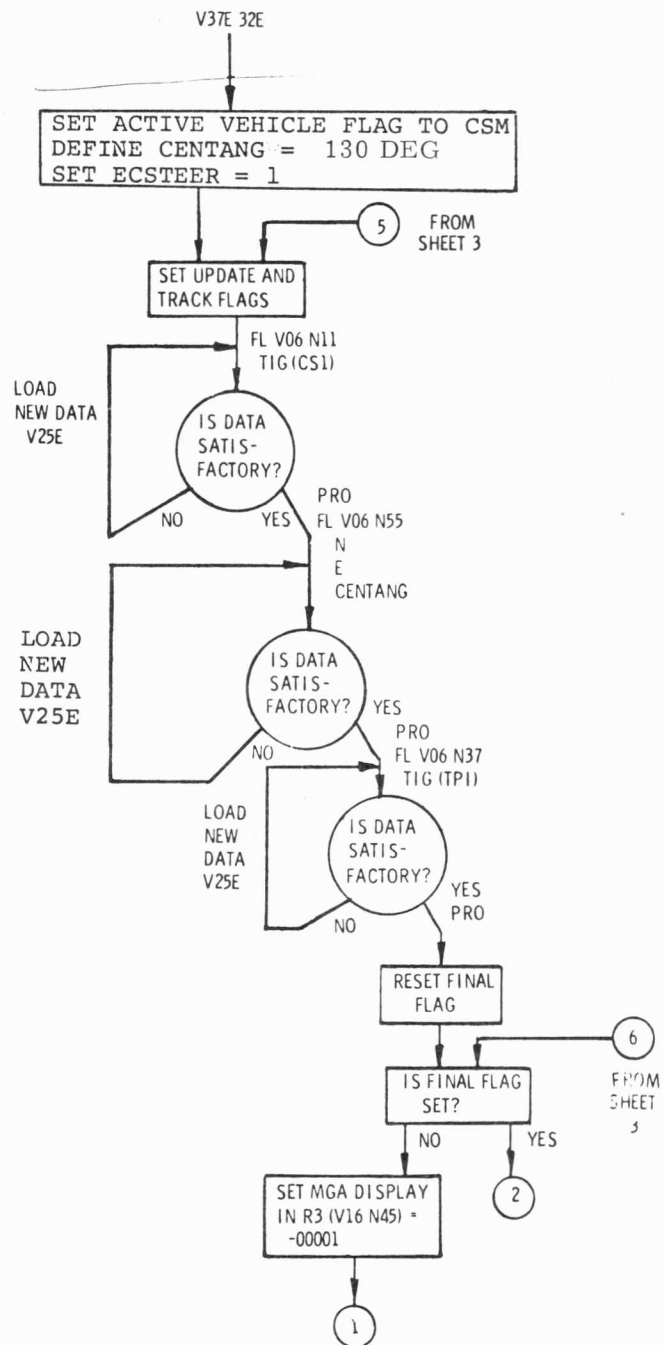


Figure 5.2.2-2. Coelliptic Sequence Initiation (CSI) (P32) (Sheet 1 of 3)

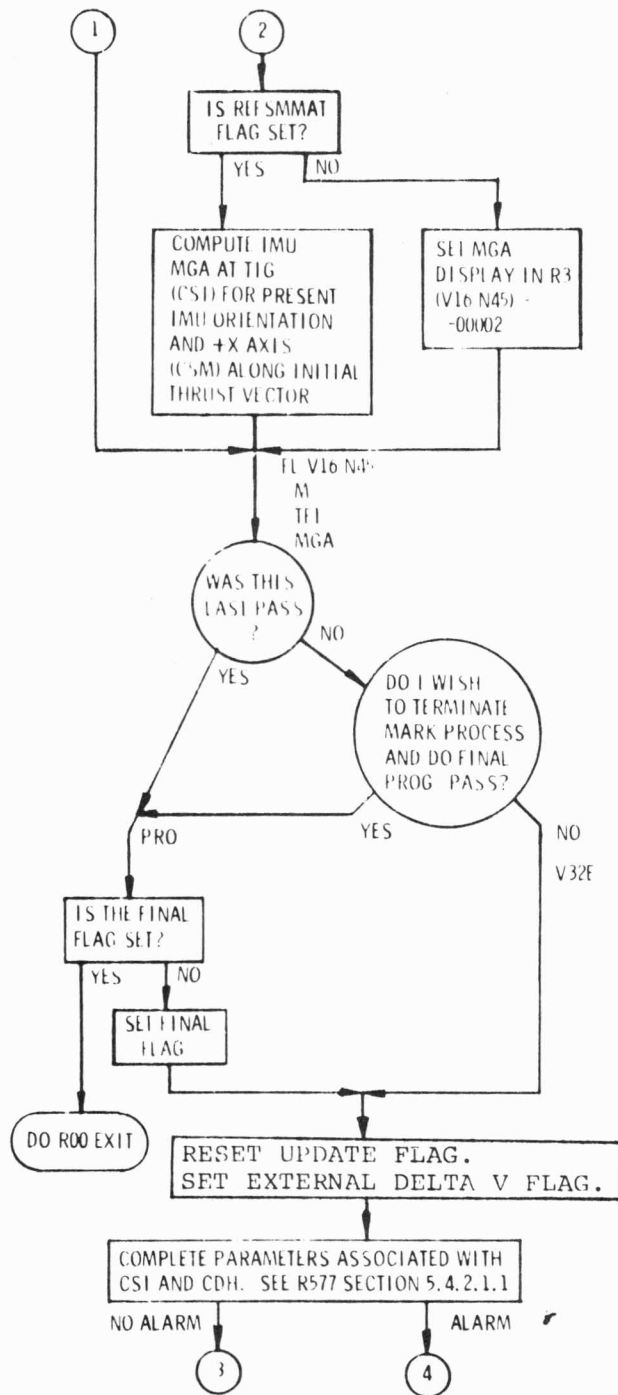


Figure 5.2.2-2. Coelliptic Sequence Initiation (CSI) (P32) (Sheet 2 of 3)

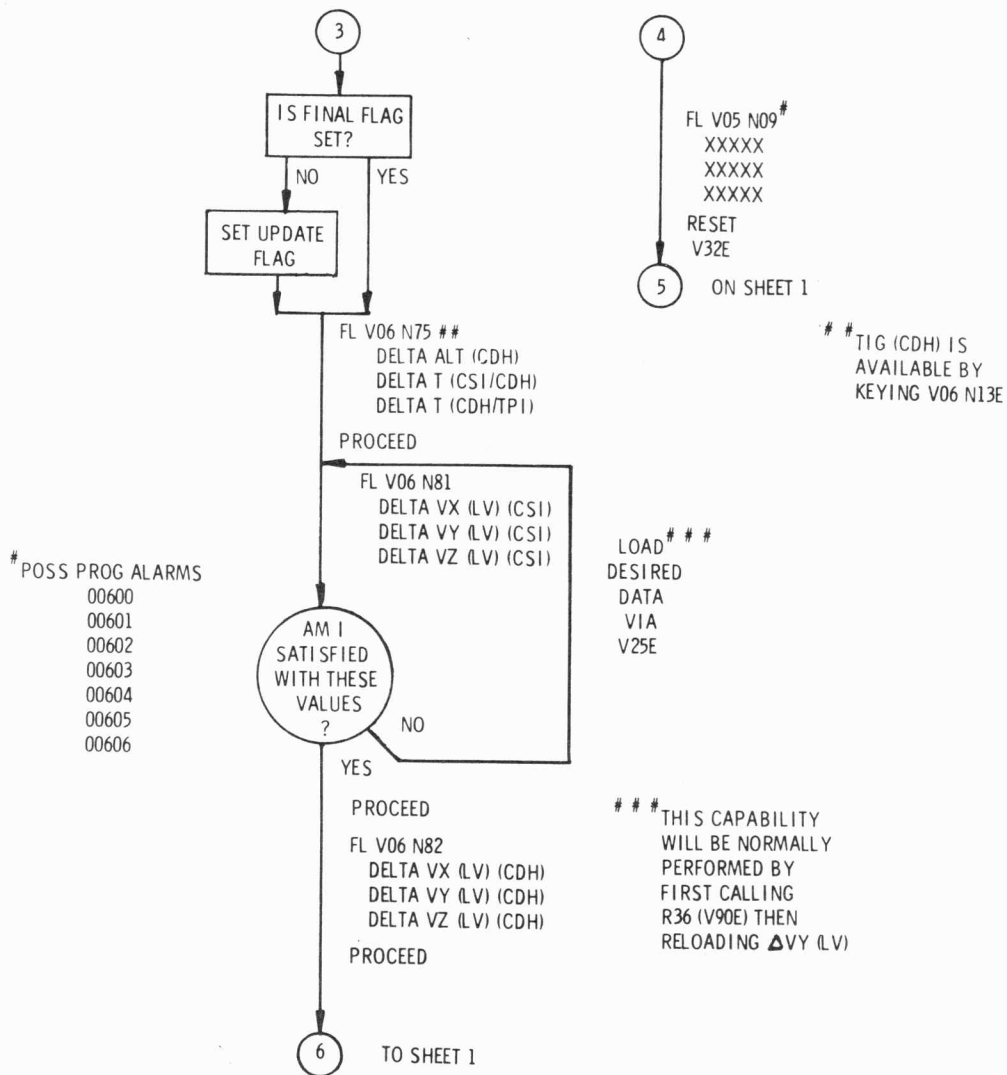


Figure 5.2.2-2. Coelliptic Sequence Initiation (CSI) (P32) (Sheet 3 of 3)

TABLE 5. 2. 2-I
P32 PROGRAM INPUTS (SHEET 1 OF 2)

Input	Identification	Display Mnemonic	DSKY	Register	Comments
1.	Time of CSI ignition	TIG(CSI)	FL V06 N11	R1 oxxxx. hr R2 oooxx. min R3 oxx. xx sec	Astronaut must load TIG(CSI)
2.	The number of the post-CSI apsidal crossing of the active vehicle at which t_{IG} (CDH) should occur, or the integral multiple of 180° transfer angle at which t_{IG} (CDH) will occur.	N	FL V06 N55	R1 xxxxx.	N is usually the first input to change when alarm conditions arise. (See section on alarms.)
3.	Elevation angle. The angle between the CSM/LM LOS and the CSM local horizontal, referenced to the direction of flight. (See R577, Section 5. 4. 2, Figure 4. 2-2).	E	FL V06 N55	R2 xxx. xx	The passive vehicle can be boresighted at this angle for TPI burn. While changing E might eliminate some alarms, E should remain constant, as all chart solutions depend on a particular E-angle.
4.	180-degree option	CENTANG	FL V06 N55	R3 00000, unless changed by astronaut V23ENTR	Loading any non-zero value into R3 will produce a CDH burn at a transfer angle from CSI of N times 180 deg.

TABLE 5.2.2-I
P32 PROGRAM INPUTS (SHEET 2 OF 2)

Input	Identification	Display Mnemonic	DSKY	Register	Comments
5.	Time of TPI ignition	TIG(TPI)	FL V06 N37	R1 oxxxx. hr R2 oooxx. min R3 oxx.xx sec	Astronaut must load t_{IG} TPI. t_{IG} (TPI) minus t_{IG} (CSI) ought to be at least 70 minutes for lunar orbit, when the 180-degree option is used. An absolute minimum would be 25 minutes. If N is increased, t_{IG} (TPI) must be increased

NOTE: The astronaut should terminate all these input displays with a PRO keystroke. If at any time the astronaut wishes to change the displayed values, he may load new ones by first keying in the appropriate load verb.

PAD. If an alarm occurs, the program should be recycled to check input. If input was good, the procedures described in the section on alarms should be followed. If the solution appears bad although no alarms have occurred, the program must be reselected via VERB 37 ENTR 32 ENTR to check input.

Table 5.2.2-II lists P32 output. VERB 16 NOUN 45 is both the first and the last output display; its purpose is to show the status of rendezvous navigation in the CMC. R1 shows the number of marks incorporated since the latest significant event in P20.*

R1 can be used to indicate when the W-matrix should be reinitialized, and how many more marks should be taken with the current W-matrix, as specified by mission procedures.

R2 shows how much time is left before ignition to take marks and perform final P32 computation. R3 indicates whether the CMC will accept marks. If R3 equals -00001, then final computations have not been made by the CMC and marks will be incorporated if taken during any flashing display. If the astronaut wishes to terminate the marking process and use the current estimate of the state vector in the CMC, he should key PRO in response to a VERB 16 NOUN 45 display. After such a keystroke, no more marks will be incorporated by the CMC. The computer will calculate the burn parameters for a final time, display the various other outputs and then redisplay VERB 16 NOUN 45. At this time, the IMU status is indicated in R3. If alignment is unknown, R3 equals -00002. Otherwise, the MGA at t_{IG} (CSI) will be shown as a positive number. Having once keyed PRO as a response to VERB 16 NOUN 45, a second PRO response will terminate the program via Routine 00. [Recycling, using a VERB 32 ENTR response at this point is useless because no parameters will change (no marks can be accepted); the astronaut must wade through the other outputs before he can reach Routine 00.]

Output 4, ΔH_{CDH} , is critical to the operation of the pre-TPI routine called by P33 and P34. In particular, if the sign of ΔH_{CDH} is plus, indicating that the CM will be below the LM after CDH, then an E-angle of anything greater than 180 degrees will cause a 00611 alarm in P33 and P34. Such a situation is considered unlikely. Should it occur, sometime before final P33 computation the astronaut should key VERB 06 NOUN 55 ENTR and follow with the appropriate load verb to change E, in

* Significant events are, Rendezvous Navigation first begun (i.e., P20 keyed-in for first time), W-matrix re-initialized, AVERAGEG, P37, or P76 terminated.

TABLE 5.2.2-II
P32 PROGRAM OUTPUTS (SHEET 1 OF 2)

Output	Identification	Display Mnemonic	DSKY	Register	Comments
1.	Accumulated Marks	Mark Counters	FL V16 N45	R1 xxBxx: VHF marks, SXT marks	VERB 32 ENTR starts computation process using latest update of state vector. PRO terminates mark process and starts final computation. See expanded commentary below.
2.	Time from ignition	TFI	FL V16 N45	R2 xxBxx: min, sec maximum: 59 min, 59 sec	Indicates time available for rendezvous navigation, execution time final P32 computation and burn preparation before t_{IG} (CSI).
3.	Middle gimbal angle (see comments at right)	MGA	FL V16 N45	R3 xxx.xx deg	<p>-00001 indicates a PRO response to VERB 16 NOUN 45 has not been received.</p> <p>-00002 indicates a PRO response has been received, and the alignment of the ISS is unknown.</p> <p>+xxx.xx deg indicates a PRO response has been received and shows the (positive) MGA at TIG (CSI).</p> <p>A PRO response for a second time will allow the program to go to Routine 00.</p>

TABLE 5. 2. 2-II
P32 PROGRAM OUTPUTS (SHEET 2 OF 2)

Output	Identification	Display Mnemonic	DSKY	Register	Comments
4.	Passive vehicle altitude minus active vehicle altitude at t_{IG} (CDH).	DELTA ALT (CDH)	FL V06 N75	R1 xxxx.x n.mi.	Normal response to VERB 06 NOUN 75 is PRO.
5.*	t_{IG} (CDH) minus t_{IG} (CSI)	DELTA T(CSI/CDH)	FL V06 N75	R2 xxBxx	Computed in hours, minutes, and seconds, of which only the minutes and seconds are displayed. See expanded notes below.
6.*	t_{IG} (TPI) minus t_{IG} (CDH)	DELTA T(CDH/TPI)	FL V06 N75	R3 xxBxx	Computed and displayed same as output 5.
7.	Impulsive Δv , in local vertical coordinates, for CSI	DELTA V (LV) (CSI)	FL V06 N81	R1 xxxx.x fps X R2 xxxx.x fps Y R3 xxxx.x fps Z	Astronaut can change this vector by using VERB 25 ENTR. If unchanged, only R1 will be non-zero. A plane change can be exercised by keying R36, VERB 90 ENTR, and including the result in the Y component (R2) of the DELTA V(LV): See paragraph 5.2.7.
8.	Impulsive Δv , in local vertical coordinates, for CDH	DELTA V(LV)	FL V06 N82	R1 xxxx.x fps X R2 xxxx.x fps Y R3 xxxx.x fps Z	Calculation of DELTA V(LV) (CDH) assumes that the CSM was active at CSI.

* t_{IG} (CDH) is available by keying VERB 06 NOUN 13 ENTR

R2, to the value that the LM should use in a nominal TPI maneuver. (See paragraph 5.2.4.)

If output 4 is small (less than about 5 n. mi. magnitude), the astronaut should be prepared for a possible 00611 alarm in P33 due to excessive iterations. It is possible that varying $t_{IG}(CDH)$ will avoid such problems; therefore, if he expects such a problem, the astronaut should select P33 for preliminary calculations very soon after CSI to allow time for searching for a solution. (See paragraph 5.2.3.)

The other outputs of P32 are self-explanatory. The following facts, however, should be emphasized. The minutes part of output 5 and 6, DELTA T (CSI/CDH) and DELTA T (CDH/TPI), are displayed modulo 60. That is, if the minutes of either output 5 or output 6 are greater than 60, they are divided by 60 and the remainder is displayed. Thus, it is possible to see values in outputs 5 or 6 that appear to be less than 10 minutes, even though no alarm has been called. Simply remember that output 5 plus output 6 must equal the time interval between $t_{IG}(CSI)$ and $t_{IG}(TPI)$. If the result appears to be an hour or two less, then the above process has occurred.

P32 calculates the CSI maneuver to be only along the X-axis of local vertical coordinates. If a plane change is desired at $t_{IG}(CSI)$, the astronaut can call R36 (VERB 90 ENTR), and load the negative of the computed \dot{Y} value for the CSM into the Y component (register 2) of the DELTA V(LV). (See paragraph 5.2.7 for an explanation of R36.

Mission planning for the G flight specified that the CMC do P32 instead of P72 and simply change the sign of the burn and subtract a 1-fps bias for comparison with the LGC and chart solutions. It should be noted, however, that under such circumstances, there is no reason to expect output 8, DELTA V(LV) (CDH), to agree with the LGC output. Such agreement will only occur in P33, after CSI has occurred.

5.2.2.3 Program Coordination

Program coordination of P32 is not very complicated because P20 is usually the only program running along with it. This, again, is mission-dependent, but final computations in P32 should come 9 to 12 minutes prior to $t_{IG}(CSI)$. A minimum of 3 minutes should be allowed for final P32 computation. Final computation time could increase, however, with a poor orbital configuration. A poor configuration would exist when the LM is in an off-nominal orbit (after an abort, for instance). In such a case, a preliminary computation should be made as soon as possible to see if more time should be allowed for final P32 computation.

5.2.2.4 Procedures for Correcting Alarm Conditions

When an alarm occurs and the astronaut wishes to change some input variable, he should key VERB 32 ENTR and use the appropriate load verb when the proper display comes up. In all cases, upon occurrence of an alarm display from P32, the first source of error to be considered should be bad input. The astronaut should recycle and check his input. Other possible sources of alarms are poor orbital configuration and bad estimates of state vectors in the CMC. If the estimates of state vectors contained in the CMC are believed to be bad, procedures should be followed to correct the situation. (See paragraph 4.2.1.) The following paragraphs assume good input conditions and good CMC state vector estimates.

All alarm codes are part of flashing display VERB 05 NOUN 09. A PRO response will do nothing; VERB 32 ENTR will recycle P32, allowing different inputs; VERB 34 ENTR will force the program to go to R00.

A list of alarm codes and procedures that may allow the program to run to completion follows:

- a. Alarm code 00600 may occur if the E-angle line-of-sight from the active vehicle at TPI does not intersect the circle formed by the passive vehicle's radius at TPI.
- b. Alarm code 00601 may occur if the post-CSI pericenter altitude is insufficient.
- c. Alarm code 00602 may occur if the post-CDH pericenter altitude is insufficient.
- d. Alarm code 00603 may occur if there is insufficient time between t_{IG} (CSI) and t_{IG} (CDH).
- e. Alarm code 00604 may occur if there is insufficient time between t_{IG} (CDH) and t_{IG} (TPI).
- f. Alarm code 00605 may occur if excessive iterations are occurring—without convergence.
- g. Alarm code 00606 may occur if two successive iterations occur with a Δy greater than 1000 fps.

Alarm 00600 occurs if the active vehicle is so high relative to the passive vehicle at TPI, that it would be impossible to see the other vehicle with the given E-angle. This particular alarm will not occur in P72, using the same inputs, so one solution is to make the other vehicle do the CSI maneuver. (If that is done, however, it is conceivable that alarm 00601 or 00602 will occur, and a ground targeted maneuver

will be required.) Increasing TPI time of ignition by one orbit, and increasing N by 1 or 2 may also help. One last possibility is to advance TPI time in 15-minute increments on successive cycles of P32. This violates the precondition that TPI be in the midpoint of darkness, but it may work.

Alarm codes 00601 and 00602 will generally occur when the active vehicle is forced to go into a lower orbit to catch up in phasing with the passive vehicle. The astronaut can try any of the following: increase TPI time, modify N, have the other vehicle perform the CSI maneuver, request a phasing maneuver of ground.

Alarm code 00603 can always be avoided by using the 180-degree option (input 4 nonzero).

Should alarm 00604 occur, recycle and use the 180-degree option. Should the alarm occur again, increase the TPI time by one orbital period, retaining the 180-degree option.

Alarm 00605 is unlikely to occur. Should it occur, however, either recycle with a different N, usually increasing N by 1, or move the whole sequence up by one orbital period.

Alarm code 00606 may occur if Δt (CSI/TPI) is too small for a given configuration. Increasing TPI time should lower the $\Delta \underline{y}$.

5.2.3 P33, Constant Delta Altitude Targeting (CDH) —CMC

The Constant Delta Altitude (CDH) maneuver results in an active vehicle orbit that remains at a nearly constant radial distance from the passive vehicle orbit. A CDH maneuver is usually targeted after a CSI maneuver in order to set up conditions for the transfer phase. (Refer to paragraphs 5.2.2 and 5.2.4 for an explanation of the CSI and TPI maneuvers, respectively.)

P33 targets for a CDH maneuver, using a $t_{IG}(\text{CDH})$ supplied by the astronaut at the beginning of P33 and a $t_{IG}(\text{TPI})$ and elevation angle (E) supplied by the astronaut at the beginning of P32.* In addition to targeting for CDH, P33 uses the pre-TPI routine to find the precise time when it will be possible to do a TPI maneuver, after CDH, using the desired E-angle. This allows the Command Module (CM) pilot to plan his post-CDH actions.

The targeting of the CDH maneuver within P33 is separate from the determination of the correct $t_{IG}(\text{TPI})$. Whereas a CDH maneuver is calculated simply by equalizing the velocities in the z-direction of the local vertical coordinate system, the pre-TPI routine takes the input $t_{IG}(\text{TPI})$ and uses it as an initial estimate in an iterative search for the precise time when the elevation angle coincides with the desired E-angle.

5.2.3.1 P33 Computational Sequence

After P33 is selected, it first enables tracking and mark incorporation by setting TRACK and UPDATE flags. Then the CM computer (CMC) flashes VERB 06 NOUN 13, which requests the astronaut to supply a $t_{IG}(\text{CDH})$ for the program. Under most circumstances (unless subsequently changed by the astronaut), the time displayed will be the $t_{IG}(\text{CDH})$ computed in P32. This value should only be used if the CM performed the CSI maneuver. If the LM performed the CSI maneuver, the LM $t_{IG}(\text{CDH})$ should be keyed in. Almost immediately after the proper value is keyed in, the CMC will flash VERB 16 NOUN 45, which requests the astronaut to determine whether the next computation cycle will be a preliminary or final computation. The appropriate responses to flashing VERB 16 NOUN 45 are VERB 32 ENTR and PRO for a preliminary and a final computation, respectively.

* The CM pilot will probably use the $t_{IG}(\text{CDH})$ calculated by P32, if the CM performed the CSI maneuver. If the LM performed CSI, the CM pilot should use the $t_{IG}(\text{CDH})$ calculated by the LGC. Some alarm recovery procedures involve changing $t_{IG}(\text{CDH})$. (See paragraph 5.2.3.4.)

After a response to VERB 16 NOUN 45, the CMC prevents any mark incorporation for the duration of the succeeding calculations by resetting the UPDATE flag. These calculations can be divided into two parts. The first involves the calculation of a maneuver that will make the active vehicle orbit coelliptic with the passive vehicle orbit. The second takes the resultant orbit, and attempts to find the time when the desired E-angle exists.

The first calculation is purely analytical, and simply calculated the $\Delta \underline{v}$ necessary to make the active vehicle H [velocity along the local vertical at $t_{IG}(CDH)$] equal to the passive vehicle orbital H; that is, the H on the passive vehicle orbit at the intersection of the passive vehicle orbit and the line formed by the projection of the active vehicle's position vector into the passive vehicle's plane.

The second calculation is the pre-TPI routine. It uses the $t_{IG}(TPI)$ input into P32 as an initial estimate in an iteration scheme to find the exact time when the desired E-angle exists. If the pre-TPI routine cannot find the required time, a VERB 05 NOUN 09 alarm is flashed; the alarm code is 00611. If no alarm occurs, or if PRO is keyed in response to the flashing VERB 05 NOUN 09 display, P33 proceeds to the next display (VERB 06 NOUN 75). Before flashing this display, however, P33 determines whether the astronaut has keyed PRO in response to VERB 16 NOUN 45. If the FINAL flag is set, then he has keyed PRO; if reset, he has not, and P33 allows marks to be incorporated by setting the UPDATE flag. The VERB 06 NOUN 75 display [ΔH_{CDH} , $\Delta t(CDH/TPI)$, $\Delta t(TPI/TPI)$], follows immediately, and is followed in turn by VERB 06 NOUN 81, $\Delta \underline{v}(LV)$. If the astronaut wishes to produce a node, 90 deg after CDH, he may overwrite the contents of R2 of the NOUN 81 display with the value of $-\dot{Y}(CSM)$ computed by R36, when T (EVENT) in NOUN 16 equals $t_{IG}(CDH)$.*

The next display is VERB 16 NOUN 45. If the last computation completed was preliminary, the CM pilot will normally wait until a few more marks are incorporated before requesting a final computation. If the last computation completed was final, another PRO response to VERB 16 NOUN 45 allows the program to exit via R00.

* R36 is initiated by keying in VERB 90 ENTR; $\dot{Y}(CSM)$ is displayed in R2 of NOUN 90 in R36. Refer to paragraph 5.2.7.

5.2.3.2 Input and Outputs

A flowchart, Figure 5.2.3-1, and two tables, Table 5.2.3-I and Table 5.2.3-II, which summarize the operations of P33 follow. To understand the flowchart, the following definitions should be made:

- a. TRACK and UPDATE flags refer to P20. If TRACK flag is set, tracking is allowed. If reset, it is not allowed. If UPDATE flag is set, the state vector may be updated from navigation marks. If it is reset, no updating from marks is possible.
- b. REFSMMAT flag set indicates that the IMU alignment is known; reset, it is unknown.
- c. FINAL flag set indicates the astronaut has keyed PRO in response to VERB 16 NOUN 45. Reset means he has not. (Refer to paragraph 5.2.3.1.)

Table 5.2.3-II lists P33 output. Outputs 1, 2, and 3 are a part of VERB 16 NOUN 45, which is both the first and last output display; its purpose is to show the status of Rendezvous Navigation (P20) in the CMC. R1 shows the number of marks incorporated since the latest significant event in P20.* R2 shows how much time is left before ignition to take marks and perform the final P33 computation. R3 indicates whether the CMC will accept marks or not. If R3 equals -00001, final computations have not been made by the CMC, and marks can be incorporated during any flashing display, except the alarm display. If the astronaut wishes to terminate the marking process and use the current estimate of the state vectors in the CMC, he should key PRO in response to a VERB 16 NOUN 45 display.

After PRO is keyed, no more marks will be incorporated into the state vector until reselection of a targeting program, and the CMC will calculate the maneuver parameters for a final time, display the other outputs, and redisplay VERB 16 NOUN 45. After a final computation, the IMU status is indicated in R3 of NOUN 45. If alignment is unknown, R3 equals -00002. Otherwise, the middle gimbal angle at t_{IG} (CDH) will be shown as a positive number. Once PRO has been keyed as a response to VERB 16 NOUN 45, keying a PRO again—as a second response—will terminate the program via Routine 00. [A VERB 32 ENTR response at this point is undesirable because no parameters will change (that is, no marks will be accepted or incorporated),

* See paragraph 4.2.1 for the significance of the number of marks taken. Some examples of significant events in P20 are, Rendezvous Navigation first begun, W-matrix reinitialized, P76 terminated and AVERAGEG terminated.

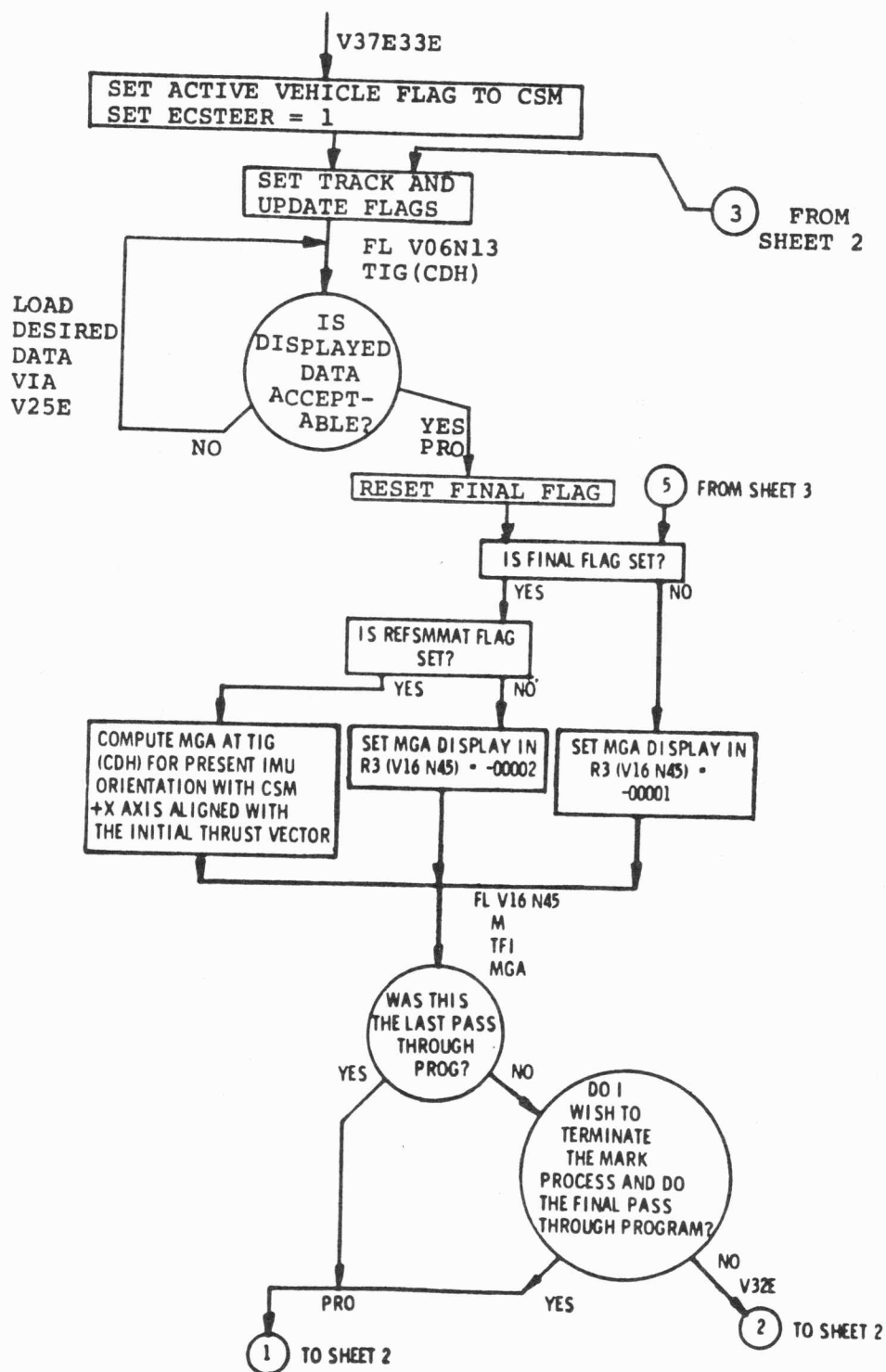
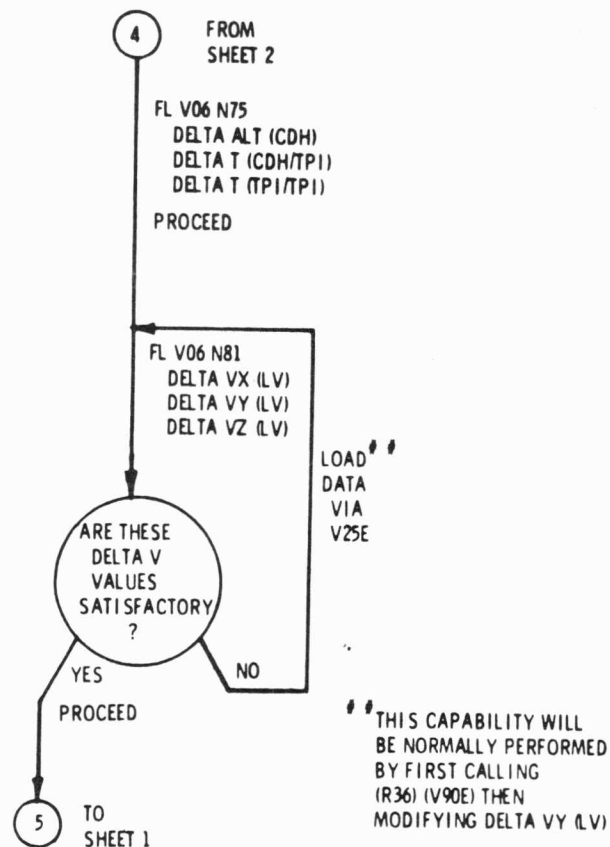


Figure 5.2.3-1. Constant Delta Altitude (CDH) Program (P33) (Sheet 1 of 3)



NOTE: GETI (TPI) AVAILABLE VIA N37.

Figure 5.2.3-1. Constant Delta Altitude (CDH) Program (P33) (Sheet 3 of 3)

TABLE 5.2.3-I
P33 INPUT

Input	Identification	Display Mnemonic	DSKY	Register	Comments
1 *	Time of CDH ignition	$t_{IG}(CDH)$	FL V06 N13	R1 oxxxx. hr R2 oooxx. min R3 oxx.xx sec	This time is initially computed by P32. It should be changed if LM did CSI, to LGC-computed t_{IG} (CDH) or to recover from alarm conditions. (See paragraph 5.2.3.4.)
2 *	Time of TPI ignition	$t_{IG}(TPI)$	None	None	This time is also an input to P32. It is used as an initial guess in the pre-TPI routine called by P33 to calculate the actual time when E (input 3) exists. Under certain conditions, it may be changed to help recover from alarm conditions. To call it up, in VERB 06 NOUN 37 ENTR. (See paragraph 5.2.3.4.)
3 *	Elevation angle	E	None	None	This angle is also an input to P32. It will be displayed in R2 of NOUN 55 if it is called up by the astronaut. It can be changed to recover from alarm conditions. (See paragraph 5.2.3.4.)

* These inputs are already available in the CMC at the time P33 is keyed in.

TABLE 5.2.3-II
P33 OUTPUT (SHEET 1 OF 2)

Output	Identification	Display Mnemonic	DSKY	Register	Comments
1	Accumulated marks	Mark counters	FL V16 N45	R1 xxBxx VHF marks, optics marks	VERB 32 ENTR starts computation process using latest update of state vector. PRO terminate mark process and completes final computation. See expanded commentary below.
2	Time from ignition	TFI	FL V16 N45	R2 xxBxx min,sec max. = 59 59	Indicates time available for rendezvous navigation before CDH burn.
3	Middle gimbal angle	MGA	FL V16 N45	R3 xxxxx	-00001 indicates a PRO response to VERB 16 NOUN 45 has not been received. -00002 indicates a PRO response has been received, and the alignment of the ISS is unknown. +xxx.xx indicates a PRO response has been received and shows the (positive) MGA at $t_{IG}(CDH)$, in 0.01 degrees. A PRO response for a second time will allow the program to go to Routine 00 (terminate).
4	Passive vehicle orbit altitude minus active vehicle orbit altitude at $t_{IG}(CDH)$	DELTA ALT(CDH)	FL V06 N75	R1 xxxx.x n. mi.	Normal response to VERB 06 NOUN 75 is PRO.

TABLE 5.2.3-II
P33 OUTPUT (SHEET 2 OF 2)

Output	Identification	Display Mnemonic	DSKY	Register	Comments
5*	$t_{IG}(TPI)$, as defined by P33, minus $t_{IG}(CDH)$.	DELTA T(CDH/TPI)	FL V06 N75	R2 xxBxx	Computed in hours, minutes, and seconds, of which only the minutes and seconds are displayed. (See expanded notes, below.) It is conceivable that this value might be negative; i.e., $t_{IG}(TPI)$, as defined by P33, is before $t_{IG}(CDH)$.
6*	$t_{IG}(TPI)$, as defined by P33, minus $t_{IG}(TPI)$, as defined by P32, earlier.	DELTA T(TPI/TPI)	FL V06 N75	R3 xxBxx	Minutes displayed modulo 60. If a PRO response was received to alarm display VERB 05 NOUN 09, R3 will be zero, and R2 will be calculated using $t_{IG}(TPI)$ as defined by P32.
7	Impulsive Δv in local vertical coordinates, for CDH	DELTA V(LV)	FL V06 N81	R1 xxxx.x fps X R2 xxxx.x fps Y R3 xxxx.x fps Z	A plane change can be made by keying in R36, VERB 90 ENTR, including the negative of the $\dot{Y}(CSM)$ result in the Y component of the DELTA V(LV). (See paragraph 5.2.7.)

* $t_{IG}(TPI)$ computed by P33 can be displayed by keying in VERB 06 NOUN 37 ENTR.

and the astronaut will have to wade through the other outputs, uselessly, before he can reach Routine 00.]

Output 4, ΔH_{CDH} , is the radial distance at CDH between the active vehicle and the passive vehicle orbit just above or below it. Output 4 is critical to recovery from alarm conditions. (See paragraph 5.2.3.4.)

Output 5 is $\Delta t(CDH/TPI)$. In trying to determine the correct $t_{IG}(TPI)$, P33 first calculates the CDH maneuver parameters, and then extrapolates the post-CDH orbit. On the basis of that orbit, the pre-TPI routine searches for the correct $t_{IG}(TPI)$. Using the computer mathematics, the post-CDH orbit can be extrapolated backwards in time, before CDH, as well as forward. It is conceivable that the proper E-angle might exist only before CDH, based on the post-CDH orbit. That is, if it were possible for the active vehicle to have been on the post-CDH orbit prior to CDH, then the proper E-angle would have existed at some time prior to CDH. Should this be the case, the computer will not be aware of the time difference, and will accept the indicated solution as a valid one. The astronaut can detect the occurrence of such a situation by observing output 5.

A negative output 5 indicates that P33 calculated TPI as coming before CDH. One of the conditions that P32 calculations must satisfy is that the time interval between CDH and TPI [$\Delta t(CDH/TPI)$] be greater than 10 minutes to allow time for rendezvous navigation after CDH. Output 5 of P33, however, can be negative, allowing no time for rendezvous navigation after CDH. Further, P33 accepts a negative solution as a valid solution. P33 also accepts an output 5 value of less than 10 minutes as a valid solution—a situation that would not provide sufficient navigation time. These situations might occur if CSI were poorly targeted, because of bad state vector estimates, or poorly executed. In any case, the CM pilot should carry out the CDH maneuver as targeted (assuming CSM-active) and select P34 with the time option (E equals 00000), with $t_{IG}(TPI)$ set according to mission procedures.

The minutes part of outputs 5 and 6 [$\Delta t(CDH/TPI)$ and $\Delta t(TPI/TPI)$] are displayed modulo 60. A large $\Delta t(TPI/TPI)$; i.e., a large difference between the input $t_{IG}(TPI)$ and the calculated $t_{IG}(TPI)$, usually means that Rendezvous Navigation after CSI has considerably changed the CMC estimate of the vehicle states. This large difference is likely to occur if CSI were poorly targeted or poorly executed.

5.2.3.3 Program Coordination

Program coordination when using P33 is straightforward. A preliminary calculation is usually made fairly soon after CSI to get some idea of the maneuver characteristics;

a final computation ought to be made 9 to 12 minutes before $t_{IG}(CDH)$, according to mission procedures. P33 can run by itself (in which case the ISS need not be operating) or it can run in conjunction with P20 (in which case marks can be incorporated during any flashing display—except an alarm display—until final computation is initiated by the astronaut by a PRO response to VERB 16 NOUN 45). The minimum time to allow for a final computation is 3 minutes.

Optimum targeting in P33 depends on relatively error-free estimates of the state vectors of the two vehicles with respect to each other. Ordinarily, there is ample time between CSI and CDH for P20 to reduce state vector errors. If SXT marks are taken in batches, as is recommended by MIT/IL, when both the SXT and the VHF are operating, P33 should be held at VERB 16 NOUN 45 until the end of a batch, and then a recycle or a final computation should be performed.

5.2.3.4 Alarms

Alarm code 00611 is the only alarm likely to occur during P33. Its occurrence indicates to the crew that the pre-TPI routine is unable to locate the time of existence of the proper E-angle. Figure 5.2.3-2 and Table 5.2.3-III summarize crew actions in response to a 00611 alarm.

In general, the recommended procedure in response to a 00611 alarm is for the CM pilot to attempt a correction of the alarm. The chart solutions, which depend on the correct E-angle at $t_{IG}(TPI)$, will then be valid, and the rates and angles after TPI will be more familiar to the astronaut. If time does not permit an attempt at correction, rendezvous can be accomplished by keying PRO in response to the flashing VERB 05 NOUN 09 alarm display. This allows the program to terminate the current cycle without again searching for the proper $t_{IG}(TPI)$. Another recycle or final computation will presumably cause another alarm, if no inputs are changed. The CM pilot should then perform the CDH maneuver as targeted (including any out-of-plane correction planned), and select P34, using the time option.

The following four circumstances could give rise to the 00611 alarm:

- a. Excessive iterations because of small ΔH_{CDH}
- b. Excessive iterations because the actual $t_{IG}(TPI)$ is more than about 30 minutes from the input $t_{IG}(TPI)$
- c. ΔH_{CDH} inconsistent with requested E
- d. Active vehicle too high above the passive vehicle.

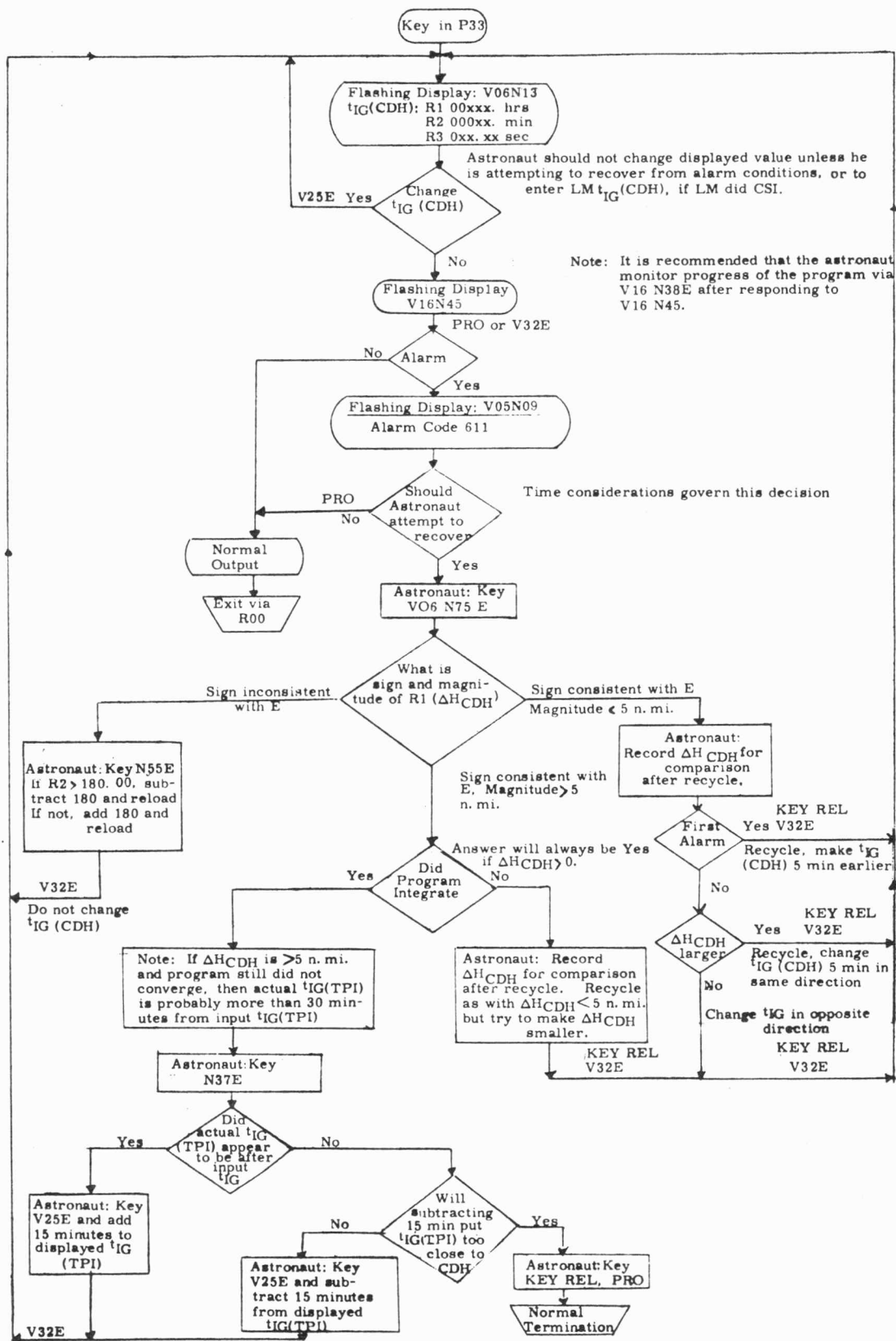


Figure 5.2.3-2. Alarm Code 00611 Conditions and Crew Actions

TABLE 5.2.3-III
ALARM RECOVERY SUMMARY

Circumstances giving rise to 00611 alarm	Diagnostic	Cause	Recovery
1. Excessive iterations	Monitor program via VERB 16 NOUN 38 ENTR. Oscillation occurs quickly. ΔH_{CDH} (R1 in NOUN 75) < 5n.mi.	Pre CSI configuration slightly off-nominal; Not serious.	Record ΔH_{CDH} for comparison if alarm recurs. Attempt to increase magnitude of ΔH_{CDH} . Recycle, changing t_{IG} (CDH) by 5 min. intervals, according to change in ΔH_{CDH}
2. Excessive iterations	Monitor program via VERB 16 NOUN 38 ENTR. Actual t_{IG} appears far from input t_{IG} (TPI). Oscillation does not occur quickly. ΔH_{CDH} not necessarily small.	Post-CSI rendezvous navigation has produced significant changes in state vector estimates.	If time permits, change t_{IG} (TPI) via VERB 06 NOUN 37 ENTR, followed by appropriate load verb.
3. SIGN of ΔH_{CDH} inconsistent with E.	R1 NOUN 75 has wrong sign. (If $E > 180^\circ$, ΔH_{CDH} must be negative. If $E < 180^\circ$, ΔH_{CDH} must be positive).	Pre-CSI configuration is off-nominal, or wrong E was loaded.	Key in VERB 06 NOUN 55 ENTR; if E in R2 is less than 180° , add 180° and reload. If R2 is greater than 180° , subtract 180° and reload.
4. Active vehicle too high relative to passive vehicle.	R1 in NOUN 75 is negative and quite large.	Post-CSI navigation produced significant changes in state vector estimates.	Recycle as in 1, but attempt to diminish magnitude of ΔH_{CDH}

The astronaut can often foresee circumstances 1 and 3 by checking the output of P32. If output 1, ΔH_{CDH} , is less than 5 n. mi., or is of the wrong sign, the CM pilot should select P33 soon after CSI to check for alarm conditions.*

Circumstances 2 and 4 could only arise (assuming CDH is used as a part of the coelliptic sequence) from a poorly targeted (due to bad onboard state vector estimates) or a poorly executed CSI maneuver. The astronaut might suspect poor targeting and poor execution if IMU alignment is known to have been poor before CSI; if insufficient marks were taken before CSI; or if CSI is known to have been poorly executed. In any case, the CMC will assume that CSI targeting and execution went well, and will not give an alarm until Rendezvous Navigation (P20) has had time to modify the relative vehicle state vectors, bringing them more in line with the true situation. That is, the CMC can only be made aware of the fact that CSI was poorly targeted or executed by a period of rendezvous navigation after CSI. Without such navigation, a 00611 alarm will not arise from circumstances 2 and 4, in spite of the fact that the real situation might warrant such an alarm. Therefore, if P20 marking indicates a large state vector error by producing excessive updates after CSI, the CM pilot should be prepared for the occurrence of a 00611 alarm in P33.

Recovery procedures are different for each circumstance causing a 00611 alarm. It is, therefore, necessary first to determine the nature of the cause. As was mentioned above, output 1 from P32 should warn the CM pilot that ΔH_{CDH} is either too small, or is inconsistent with E. But poor targeting or execution of CSI could also have produced this anomalous ΔH_{CDH} . Therefore, even if ΔH_{CDH} appeared good in P32, these circumstances should not be excluded. The first action in an attempt to recover from alarm conditions, therefore, is to examine ΔH_{CDH} , the contents of R1 of NOUN 75.

If ΔH_{CDH} is inconsistent with E, then 180 deg should be added to E (displayed as R2 in NOUN 55) if E is less than 180 deg; 180 deg should be subtracted from E if E is greater than 180 deg.

If ΔH_{CDH} is consistent with E, but is less than 5 n. mi., the astronaut should recycle (VERB 32 ENTR) and subtract 5 minutes from $t_{IG}(CDH)$, because, under most circumstances, the pre-CDH orbits are converging. If the alarm occurs again,

* If E is greater than 180 deg, ΔH_{CDH} should be negative; if E is less than 180 deg, ΔH_{CDH} should be positive.

ΔH_{CDH} should again be checked to see if it is now larger or smaller than before. If it is larger, recycle and subtract another 5 minutes. If it is smaller, then the orbits are diverging, and a later $t_{IG}(CDH)$ should be tried.

If ΔH_{CDH} is positive, greater than 5 n. mi., and consistent with E, then the actual $t_{IG}(TPI)$ lies more than about 30 minutes from the input $t_{IG}(TPI)$ supplied from P32. If ΔH_{CDH} is negative, indicating active vehicle above passive vehicle, greater than 5 n. mi., and consistent with E, then either $t_{IG}(TPI)$ lies more than about 30 minutes from the input $t_{IG}(TPI)$, or the active vehicle is too high above the passive vehicle. By monitoring the progress of the program (via VERB 16 NOUN 38 ENTR), the astronaut can determine whether the active vehicle is too high above the passive vehicle (the program does not attempt to search for E under such conditions), or whether the actual $t_{IG}(TPI)$ is too far before or after the input $t_{IG}(TPI)$.

To describe how to monitor the program, it is first necessary to describe how the pre-TPI routine works. The pre-TPI routine accepts as input the active and passive vehicle state vectors, extrapolated to the input $t_{IG}(TPI)$, the initial estimate used in the search for the actual $t_{IG}(TPI)$. At this point, the alarm conditions of E, inconsistent with ΔH_{CDH} and active vehicle too high above the passive vehicle, are tested.

If these 2 tests are satisfied, the program first determines whether the correct E-angle exists before or after the given $t_{IG}(TPI)$, and then proceeds to extrapolate the two vehicle state vectors, in steps limited to 250 sec, towards the time when the correct E-angle exists. This continues until the E-angle is reached.

When the CM pilot monitors P33, via VERB 16 NOUN 38, he will see the time associated with the vehicle state vectors. The displayed time, expressed in hours, minutes and seconds, will be augmented until the input TPI time is reached and the pre-TPI routine is entered. Then it will increase, if the actual $t_{IG}(TPI)$ is after the input $t_{IG}(TPI)$, or diminish if the opposite is true.

If the active vehicle is too high above the passive vehicle, or if E is inconsistent with ΔH_{CDH} , the program will not iterate after input $t_{IG}(TPI)$ is reached. If ΔH_{CDH} is too small, the times will probably oscillate very soon after the input $t_{IG}(TPI)$ is reached, and continue to oscillate for quite a while. If the actual TPI time is too far from the input TPI time, i.e., greater than approximately 30 minutes, then the displayed time will move quite far from the input $t_{IG}(TPI)$ before oscillation begins.

If the active vehicle is too high relative to the passive vehicle, the CM pilot should recycle and augment $t_{IG}(CDH)$, in an attempt to diminish ΔH_{CDH} . If an alarm occurs again, ΔH_{CDH} should be checked to see if it is smaller (in which case another recycle and a second augmentation of $t_{IG}(CDH)$ is in order), or larger (in which case $t_{IG}(CDH)$ should be diminished).

If actual $t_{IG}(TPI)$ is far from input $t_{IG}(TPI)$, the input $t_{IG}(TPI)$, available in NOUN 37, should be moved in the direction of the actual $t_{IG}(TPI)$.

5.2.3.5 Restarts

A restart that occurs during the operation of P33 will only cause a time loss (the maximum time loss is just less than the time required for final computation), not a loss of validity in the solution.

5.2.4 P34, Transfer Phase Initiation (TPI) —CMC

P34 targets for the Transfer Phase Initiation maneuver (TPI), a part of the rendezvous sequence. The TPI maneuver occurs after the coelliptic sequence maneuvers (CSI and CDH), which are designed to produce a configuration at TPI with two important characteristics: coelliptic orbits, and a particular elevation angle, E , between the active-to-passive LOS and the $+x$ direction of the local vertical coordinate frame at $t_{IG}(TPI)$. If the coelliptic sequence is successful in producing such a configuration, the second part of the rendezvous sequence, the transfer phase, has the following four desirable properties:

- a. The closing rate is rather slow
- b. The changes in the LOS elevation angle are predictable
- c. The direction of the thrust vector for the TPI maneuver very nearly coincides with the LOS
- d. The magnitude of the change in velocity, measured in feet per second, is very close to twice the difference in altitude between the orbits, measured in n. mi.

These properties allow for easy monitoring of the transfer phase, and easy astronaut takeover in the event of computer malfunction during and after the TPI maneuver.

P34 must interface with two other programs, P20, Rendezvous Navigation, and P40 or P41, the thrusting programs. P20 is needed after every maneuver in the rendezvous sequence to improve the estimate of the state vectors. The thrusting programs carry out the maneuver targeted by P34. A preliminary estimate of the maneuver can be computed before navigation is completed; marks can be incorporated during some flashing displays, until the final computation is initiated.

P34 is divided into two computation phases. The first sets up the input to the second. The first phase can be done one of two ways. It either accepts a desired E -angle and iterates to find the time when the angle exists, or it accepts a time and calculates the E -angle existing at that time.

The second phase takes the calculated (or requested) E -angle and calculated (or requested) time, and the requested CENTANG, and calculates a Lambert maneuver designed to effect intercept. The maneuver calculation can be done in one of two ways. The target vector is determined either conically, or with a specified number of precision offsets.

5.2.4.1 P34 Computational Sequence

When P34 is called, it first enables tracking and mark incorporation by setting TRACK and UPDATE flags. Then the CMC flashes VERB 06 NOUN 37, which requests the astronaut to supply a t_{IG} (TPI) for the program. Under most circumstances, the time displayed will be that computed by P33. If a 00611 alarm out of P33 was bypassed, then the time displayed will be that input by the astronaut to P32 (unless it was subsequently changed by the astronaut). VERB 06 NOUN 55 is then displayed. NOUN 55 allows the astronaut to exercise the two choices available in P34: the E-angle-time (in R2, E does not equal 0 or E equals 0) choice, and the conic-precision offset targeting (in R1, NN equals 0 or NN does not equal 0) choice. After VERB 06 NOUN 55, P34 flashes VERB 16 NOUN 45, which allows the astronaut to monitor the progress of Rendezvous Navigation by displaying the mark counters. VERB 16 NOUN 45 also requests the astronaut to determine whether the next cycle will be a preliminary or a final computation. The appropriate responses are, VERB 32 ENTR and PRO, respectively.

After a response to VERB 16 NOUN 45 is made, the CMC prohibits further mark incorporation for the duration of the succeeding calculations by resetting the UPDATE flag. These calculations can be divided into two parts. If the E-option is exercised, by loading + xxx.xx (where xxx.xx is nonzero) into R2, the first part of P34 is the pre-TPI routine, which determines exactly when the correct E-angle exists. If the proper time is found, then P34 flashes VERB 06 NOUN 37. If P34 cannot find the proper time, alarm 00611 occurs as a part of VERB 05 NOUN 09. If the time option is exercised, by loading +00000 in R2 of NOUN 55, the first part of P34 will take the input t_{IG} (TPI) and compute the E-angle existing at that time and flash the result as part of the VERB 06 NOUN 55 display.

After either E or the proper t_{IG} (TPI) is calculated and displayed, P34 targets an intercept course. If the current pass is the final computation, the impulsive $\Delta \underline{y}$ is displayed in local vertical coordinates, (VERB 06 NOUN 81) which allows the astronaut to overwrite R2 with $-\dot{Y}$ (CSM), from R36, to produce a node 90-deg later. Should R2 be written over, P34 recomputes the target vector accordingly. The $\Delta \underline{y}$ is displayed in LOS coordinates (VERB 06 NOUN 59) for recycles and final computation.

VERB 16 NOUN 45 follows almost immediately. If the last computation was preliminary, the CM pilot will probably wait until a few more marks are incorporated before requesting a final computation. If the last computation was final, keying PRO allows P34 to exit via R00.

5.2.4.2 Inputs and Outputs

A flowchart, Figure 5.2.4-1, and two tables, Table 5.2.4-I and Table 5.2.4-II, describing P34 input and output follow. To understand the flowchart, the following facts must be known.

1. TRACK and UPDATE flags refer to Rendezvous Navigation. If the TRACK flag is set, tracking is allowed. If the TRACK flag is reset, tracking is not allowed. If the UPDATE flag is set, marks will be incorporated; if it is reset, marks can be taken, but will not be incorporated.
2. FINAL flag set means a PRO response to a flashing VERB 16 NOUN 45 display has been received; reset, a PRO response has not been received.

Input 1, $t_{IG}(TPI)$, will ordinarily be retained as displayed. This value for $t_{IG}(TPI)$ is usually the same as the one computed in P33. If everything has gone well, the input $t_{IG}(TPI)$ should be quite close to the time when the actual elevation angle coincides with the desired E (input 3).

Input 2, NN, governs which method of calculation the program will use in the second computation phase. If NN equals 00000, the program will calculate a conic approximation of the correct TPI maneuver. In the lunar gravitational sphere, the accuracy of this method is equivalent to target offsetting. Its advantage over the other method, called when NN does not equal 00000, is its speed in obtaining an answer. For earth-orbital rendezvous, NN equals 00002 is required for a correct answer because of oblateness effects, in spite of the time consumed in using it. (Refer to Table 5.2.4-I.)

Input 3, E, governs which method of calculation the program will use in the first computation phase. If E equals 00000, the program will calculate a maneuver appropriate to the input $t_{IG}(TPI)$. If E does not equal 00000, the program will accept the input number as an angle, to the nearest 0.01 degree, and use the input $t_{IG}(TPI)$ (input 1) as an initial estimate for the pre-TPI routine.

Input 4, CENTANG, indicates the orbital central angle through which the passive vehicle must pass between $t_{IG}(TPI)$ and intercept. Implicit in CENTANG is a target vector and a transfer time, which the Lambert targeting routine uses as input.

Table 5.2.4-II lists P34 output. Outputs 1-3 are contained in VERB 16 NOUN 45, which is both the first and the last output display. The purpose of VERB 16 NOUN 45 is to show the status of P20 in the CMC. R1 shows the number of marks incorporated

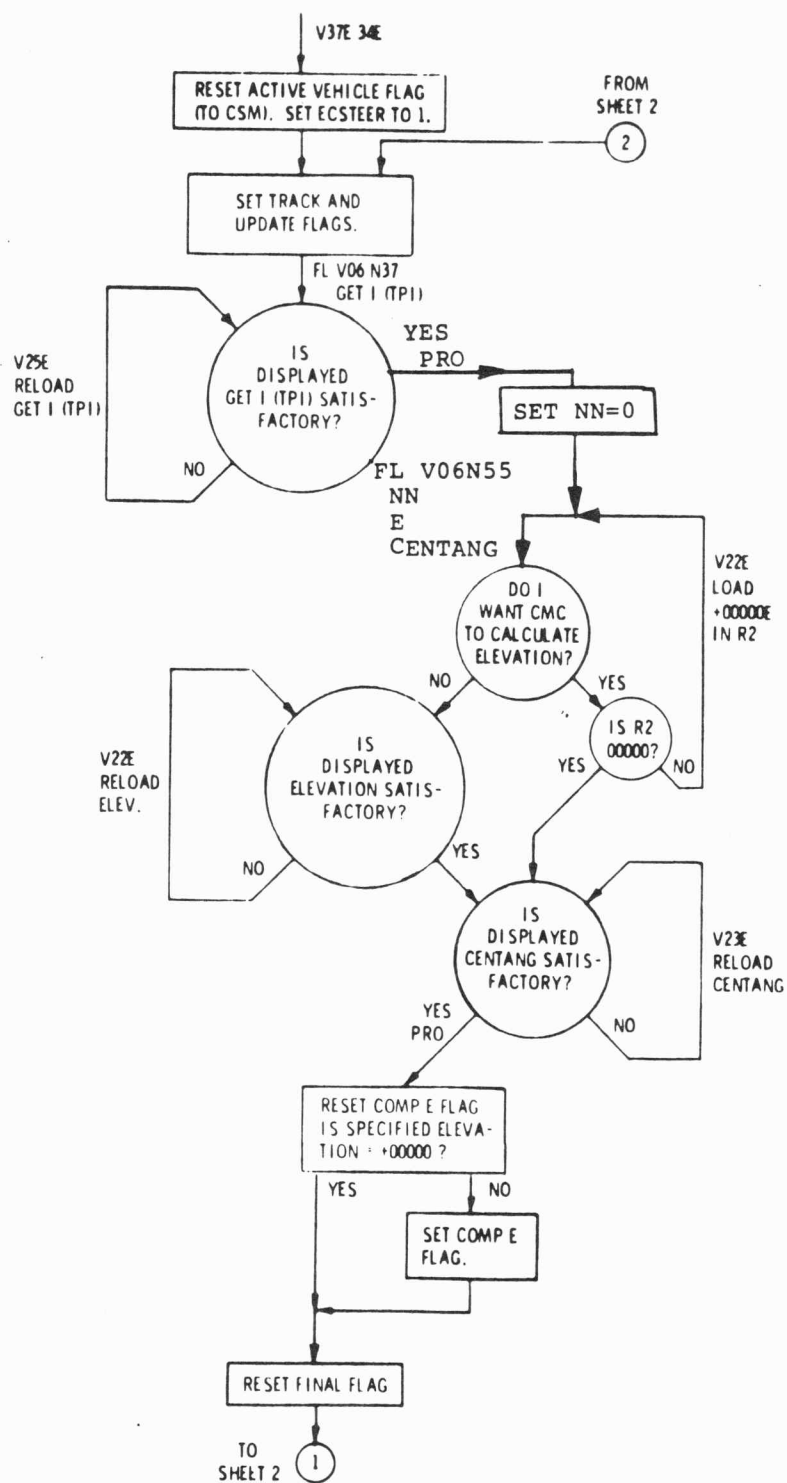


Figure 5.2.4-1. Transfer Phase Initiation Program (P34) (Sheet 1 of 3)

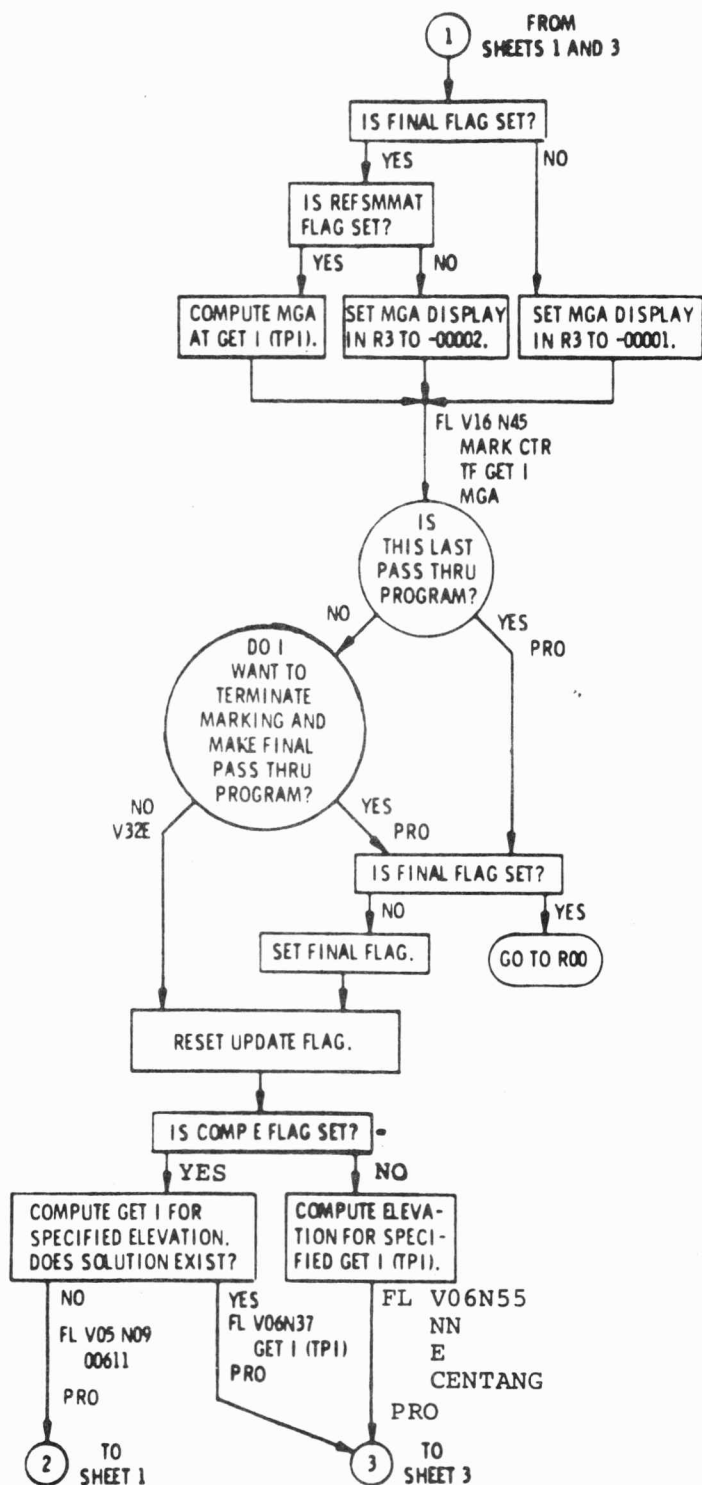


Figure 5.2.4-1. Transfer Phase Initiation Program (P34) (Sheet 2 of 3)

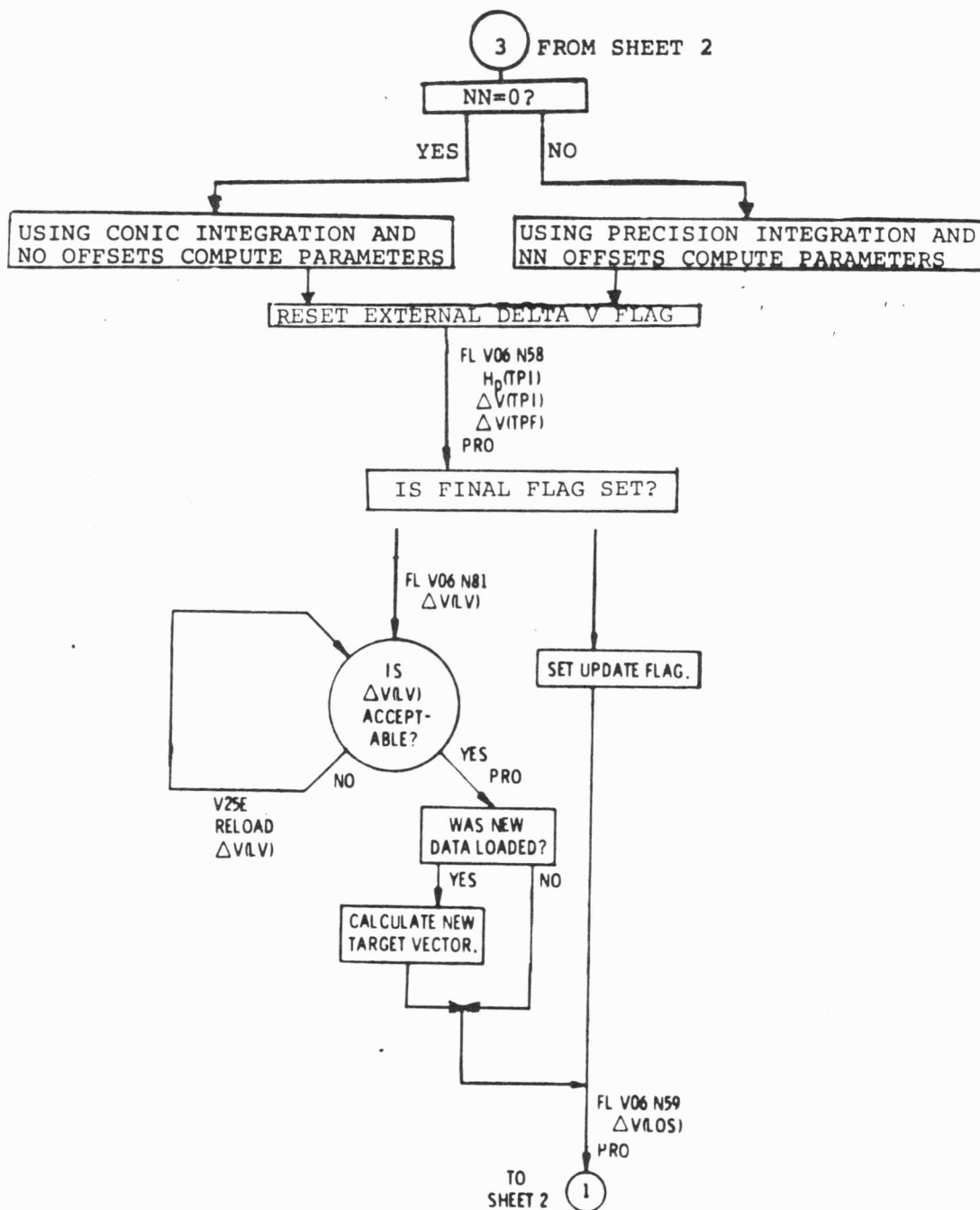


Figure 5.2.4-1. Transfer Phase Initiation Program (P34) (Sheet 3 of 3)

TABLE 5. 2. 4-I
P34 INPUT

Input	Identification	Display Mnemonic	DSKY	Register	Comments
1	TPI time of ignition	TIG(TPI)	FL V06 N37	R1 oxxxx. hr R2 oooxx. min R3 oxx. xx sec	This will initially flash the value computed by P33 (unless subsequently changed by the astronaut). If the E-option is used, input 1 will be used as an initial guess as the program tries to locate the time when the elevation angle coincides with the desired E (input 3). If the time-option is exercised, then input 1 will be the actual t_{IG} (TPI).
2	Conic-precision switch; if positive, number of offsets to be used in Lambert targeting.	NN	FL V06 N55	R1 xxxxx	If input 2 = 00000, the recommended value for lunar orbital activities, the very fast conic integration will be used to calculate the TPI maneuver. Input 2 = +00002 is recommended for earth orbit activities to account for oblateness effects. Any positive number will cause the program to use precision offsets.
3	E-option-time-option switch; if nonzero, desired E angle	E	FL V06 N55	R2 xxx. xx deg	If input 3 = 00000, program will accept input 1 as desired t_{IG} (TPI), and calculate a TPI maneuver for that time. If input 3 \neq 00000, the program will use input 1 as an initial guess in an attempt to find the time when the elevation angle coincides with input 3.
4	Central angle through which the passive vehicle must pass from t_{IG} (TPI) to intercept.	CENTANG	FL V06 N55	R3 xxx. xx deg	This is set according to mission procedures.

TABLE 5.2.4-II
P34 OUTPUT (SHEET 1 OF 3)

Output	Identification	Display Mnemonic	DSKY	Register	Comments
1	Accumulated Marks	Mark Counters	FL V16 N45	R1 xxBxx VHF marks, optics marks	VERB 32 ENTR starts computation process using latest update of state vectors. A PRO terminates mark incorporation and completes final computation.
2	Time from Ignition	TFI	FL V16 N45	R2 xxBxx min, sec maximum: 59 min, 59 sec	Indicates time available for rendezvous navigation before TPI burn.
3	Middle Gimbal Angle	MGA	FL V16 N45	R3 xxxxx	-00001 indicates a PRO response to VERB 16 NOUN 45 has not been received. -00002 indicates a PRO response has been received, and the alignment of the ISS is unknown. +xxxxx indicates a PRO response has been received and shows the (positive) MGA at t_{IG} (TPI), in 0.01 degrees. A PRO response for a second time will allow the program to go Routine 00.
If the astronaut requested the time option by putting in +00000 for E (input 3), then outputs 4, 5 and 6 will follow outputs 1, 2 and 3, and then output 8 will follow. Otherwise 4, 5, and 6 will be skipped, and 7 will follow 1, 2, and 3.					
4	Number of target offsets	NN	FL V06 N55	R1 xxxxx	This register will display whatever was put in by the astronaut.
5	Elevation angle. (see input 3 for definition)	E	FL V06 N55	R2 xxx.xx deg	This register will now display the actual elevation angle for the given t_{IG} (TPI).

TABLE 5.2.4-II
P34 OUTPUT (SHEET 2 OF 3)

Output	Identification	Display Mnemonic	DSKY	Register	Comments
6	Orbital central angle of the passive vehicle during transfer from t_{IG} (TPI) to intercept.	CENTANG	FL V06 N55	R3 xxx.xx	This register will display whatever was put in by the astronaut.
7	Calculated time ignition for TPI	TIG(TPI)	FL V06 N37	R1 ooooo. hrs R2 ooooo. min R3 oxx.xx sec	When the astronaut wishes to do TPI with a certain E-angle, the program searches for a time when that E-angle exists. Output 7 is that time.
8	Perigee altitude	PER ALT	FL V06 N58	R1 xxxx.x n. mi.	This perigee altitude is altitude above pad radius, for the earth, or altitude above the latest landing site, for the moon.
9	Impulsive change in velocity for TPI	ΔV (TPI)	FL V06 N58	R2 xxxx.x fps	P34 and P35 burns are Lambert maneuvers.
10	Impulsive change in velocity for TPF	ΔV (TPF)	FL V06 N58	R3 xxxx.x fps	
11	Impulsive change in velocity vector in local vertical coordinates	ΔV (LV)	FL V06 N81	R1 xxxx.x fps X R2 xxxx.x fps Y R3 xxxx.x fps Z	Displayed only after final computation. Crew has the option at this time to redefine the $\Delta \vec{v}$ (LV) components for the subsequent thrusting maneuver.

TABLE 5.2.4-II
P34 OUTPUT (SHEET 3 OF 3)

Output	Identification	Display Mnemonic	DSKY	Register	Comments
12	Impulsive change in velocity vector in LOS coordinates.	$\Delta V(\text{LOS})$	FL V06 N59	R1 xxxx.x fps X R2 xxxx.x fps Y R3 xxxx.x fps Z	<p>If the astronaut wishes to produce a mode 90⁰ after TPI, he should select the rendezvous out-of-plane display, Routine 36 (VERB 90 ENTR), and then overwrite R2 of Δv (LV), using the appropriate load verb, with - Y (CSM)</p> <p>LOS coordinates are defined in paragraph 5.2.4.2.</p>

since the last significant event in P20.* R2 shows how much time is left to take marks and perform the final P34 computation before ignition. R3 indicates whether the CMC will accept marks. If R3 equals -00001, then final computations have not been made by the CMC, and marks can be incorporated during some flashing displays. If the astronaut wishes to terminate the marking process and use the current estimate of the state vectors in the CMC for a final P34 solution, he should key PRO in response to a VERB 16 NOUN 45 display. After PRO, no more marks will be incorporated in the CMC state vector. The computer will calculate the maneuver parameters for a final time, display the various other outputs, and then redisplay VERB 16 NOUN 45. After a final computation, the IMU status is indicated in R3. If alignment is unknown, R3 equals -00002, otherwise, the middle gimbal angle (contents of R3) at t_{IG} (TPI) will be shown as a positive number. A second PRO response to VERB 16 NOUN 45 will terminate the program via Routine 00. The astronaut should not attempt to recycle (by keying in VERB 32 ENTR) at this point, because no parameters will change; that is, no marks will be incorporated, and the astronaut will be forced to uselessly wade through the other outputs before reaching Routine 00.

Depending on the mode used, either a VERB 06 NOUN 55 or a VERB 06 NOUN 37 will flash after all but the final VERB 16 NOUN 45 displays. If the time option (E equals 00000) was exercised, the program will compute E for the specified t_{IG} (TPI), and display it as R2 (output 5) in a VERB 06 NOUN 55 display. Registers 1 and 3 will be identical with inputs 2 and 4, supplied by the astronaut. If the E option is exercised, output 7, the computed t_{IG} (TPI), will be flashed in a VERB 06 NOUN 37 display.

After either the NOUN 55 or the NOUN 37 display, the program calculates the Δy required for the TPI maneuver. When the thrust vector is calculated, the program flashes a VERB 06 NOUN 58 display, containing outputs 8, 9 and 10 in R1, R2 and R3, respectively. Refer to Table 5.2.4-II for an explanation of these outputs, which represent the magnitudes of the initial and final maneuvers of the transfer phase. Output 11, flashed only after final computation, and output 12 show the thrust vector displayed first in the local vertical coordinates, at t_{IG} (TPI), and then in LOS coordinates. (For a description of the local vertical coordinate system, refer to Document No. R-577, paragraph 5.1.4.2.) The LOS coordinate system can be described as follows:

* Refer to paragraph 4.2.1 for the significance of the number of marks taken. Some examples of significant events in P20 are P20 originally keyed in, W-matrix reinitialized, AVERAGEG terminated, and P76 terminated.

LOS Coordinate System

$$\begin{aligned}\underline{X} \text{ (LOS)} &= \text{unit } (\underline{r}_P - \underline{r}_A) \\ \underline{Y} \text{ (LOS)} &= \text{unit } [((\underline{r}_A \times \underline{v}_A) \times \underline{X} \text{ (LOS)}) \times \underline{X} \text{ (LOS)}] \\ \underline{Z} \text{ (LOS)} &= \text{unit } [\underline{X} \text{ (LOS)} \times \underline{Y} \text{ (LOS)}]\end{aligned}$$

In other words, the active-passive LOS is along the +X(LOS) axis. Y(LOS) is perpendicular to X(LOS), in the plane formed by X(LOS) and Y(LV). Z(LOS) completes the right-handed system.

As was mentioned above, VERB 16 NOUN 45 is flashed after final computation, before the program terminates, and R3 equals either -00002 or the positive middle gimbal angle at t_{IG} (TPI).

5.2.4.3 Program Coordination

Like all the rendezvous targeting programs, P34 can be used in conjunction with P20. Although P20 requires that the ISS be running and aligned, P34 does not. SXT marks can be taken via R21 during any P34 flashing display; VHF marks can accumulate throughout the program. Marks will not be incorporated, however, after the astronaut has keyed PRO in response to a VERB 16 NOUN 45 display, nor during any flashing VERB 06 NOUN 55 or NOUN 37 after any flashing VERB 16 NOUN 45 display.

The P34/P40 or P41 interface is automatic, and need not concern the astronaut.

5.2.4.4 Program Limitations

Under certain conditions, such as a small ΔH_{CDH} , the program may not be able to find the desired E-angle. This will cause a 00611 alarm code to be flashed as part of a VERB 05 NOUN 09 display. If the desired E-angle cannot be found, the procedures outlined in paragraph 5.2.4.5 should be followed. The time option will always produce a solution for rendezvous.

5.2.4.5 Alarms

Alarm 00611 is the only alarm code likely to occur during P34. The circumstances under which alarm 00611 might occur are described in paragraph 5.2.3.4. Unless CDH is poorly performed, this alarm should occur during P33 when the CM pilot is likely to have more time to search for a solution. In a time-critical situation like the period between CDH and TPI, the iteration process used to find t_{IG} (TPI) is

usually too lengthy to be used more than once. Therefore, if a 00611 alarm should occur in P34, it is recommended that the CM pilot recycle (by keying in VERB 32 ENTR), use the time option (input 3, E equals 00000), and leave the other inputs unchanged.

5.2.4.6 Restarts

P34 is protected against restarts. If one should occur during P34 operation, no loss of accuracy, but a loss of time—equal at most to the time required for a final computation—would occur.

5.2.5 P35, Transfer Phase Midcourse (TPM) Targeting - CMC

P35 targets a midcourse correction for the transfer phase of the rendezvous sequence. All of the P35 inputs are available in the computer at the time it is selected; the astronaut need not key in anything but P35, itself. The inputs to P35 are as follows:

- a. Active and passive vehicle state vectors, as updated by P20, if it is running
- b. Time of intercept, as calculated by P34
- c. Time of ignition, defined as follows:
Current time + A
where A is pad-loaded, or loaded via P27.
- d. NN, the conic-precision offset target switch, input in P34 as R1 of NOUN 55.

Given these inputs, P35 targets a midcourse correction using the Lambert routine. It computes the required Lambert target vector and transfer time and displays the required impulsive Δy , both in local vertical coordinates and in LOS coordinates (if the computation was a final computation). P35 also allows the astronaut to monitor the progress of P20 by flashing the standard VERB 16 NOUN 45 display described in paragraph 5.2.4.

Like all the other rendezvous targeting programs, P35 must interface with two other major modes, P20 and P40/P41. P20 can run along with P35. Marks with the SXT can be taken and incorporated during any flashing display before final computation is requested by a PRO response to VERB 16 NOUN 45; VHF marks can accumulate until a PRO indicates final computation. P35 must initialize registers for P40/P41 (ECSTEER, for instance), but this is done automatically, without the aid of the astronaut. No alarms are expected during P35.

5.2.5.1 Options

P35 provides one choice. The astronaut must decide whether he wishes a preliminary or a final computation of the midcourse correction Δy that P40/P41 will use. This decision will be based on mission procedures and the status of Rendezvous Navigation (P20) (i.e., whether sufficient marks have been incorporated or not).

5.2.5.2 P35 Computational Sequence

The P35 computational sequence is not complicated. The inputs are obtained from various computer locations and the target vector is calculated, either conically or

using precision offsets, as specified by NN. (Refer to paragraph 5.2.4.) Figure 5.2.5-1 is a flowchart of P35. Tables 5.2.5-I and 5.2.5-II show P35 input and output, respectively.

When P35 is selected, it first enables tracking and mark incorporation by setting TRACK and UPDATE flags. Then the CM computer flashes VERB 16 NOUN 45, the standard monitor for P20. It should be noted here that R2, showing the time from ignition (TFI), displays a positive number the first time VERB 16 NOUN 45 comes up. In actual fact, the time shown is time from ignition of the last maneuver (or maneuver calculation), because the registers containing $t_{IG}(TPM)$ are not loaded until some response is made to VERB 16 NOUN 45. This allows the astronaut to space out the midcourse maneuvers according to mission planning.

After a PRO or VERB 32 ENTR response is made to the VERB 16 NOUN 45 display, a pad-loaded or uplinked increment, A, is added to the time when the response was made to produce the time for the TPM ignition (even if the current cycle is a preliminary computation). Then, the CMC uses the time of intercept computed in P34 to extrapolate the target vector. If NN was nonzero in P34, indicating a certain number of precision offsets, P35 will use that number of precision offsets in computing the target vector. If NN was zero in P34, P35 will compute the target vector using conic integration.

After the target vector and corresponding Δy have been computed, if the current computation is a final one, P35 flashes the Δy in local vertical coordinates via VERB 06 NOUN 81. This allows the astronaut to overwrite R2 with $-\dot{Y}(CSM)$ computed by R36. Should R2 be changed, P35 will recompute the target vector accordingly. The Δy is displayed in LOS coordinates, whether the computation was final or not.

The final display, common to all targeting routines, is VERB 16 NOUN 45. If the last computation was preliminary, the CM pilot will probably wait until a few more marks have been incorporated before requesting a final computation. If the last computation was final, keying PRO will allow P35 to exit via R00.

5.2.5.3 Restrictions and Limitations

If input 4, CENTANG, to P34 was greater than 180 deg, the transfer angle from position at $t_{IG}(TPM)$ to the target vector (available from VERB 06 NOUN 52) might be in the range 165 to 195 deg. If it is, P35 will rotate the target vector into the plane of the active vehicle. This will result in the loss of any out-of-plane correction. If the transfer angle is in the range of 165 to 195 deg, it is recommended that the

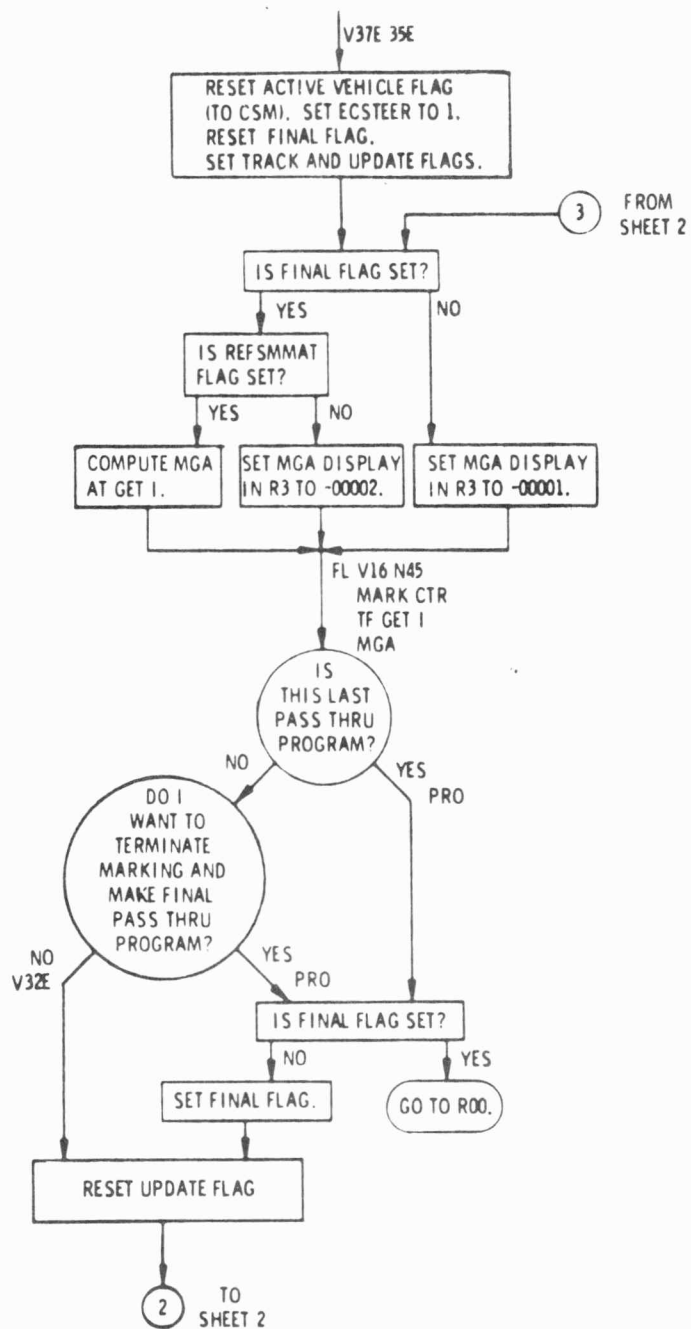


Figure 5.2.5-1. Transfer Phase Midcourse Program (P35) (Sheet 1 of 2)

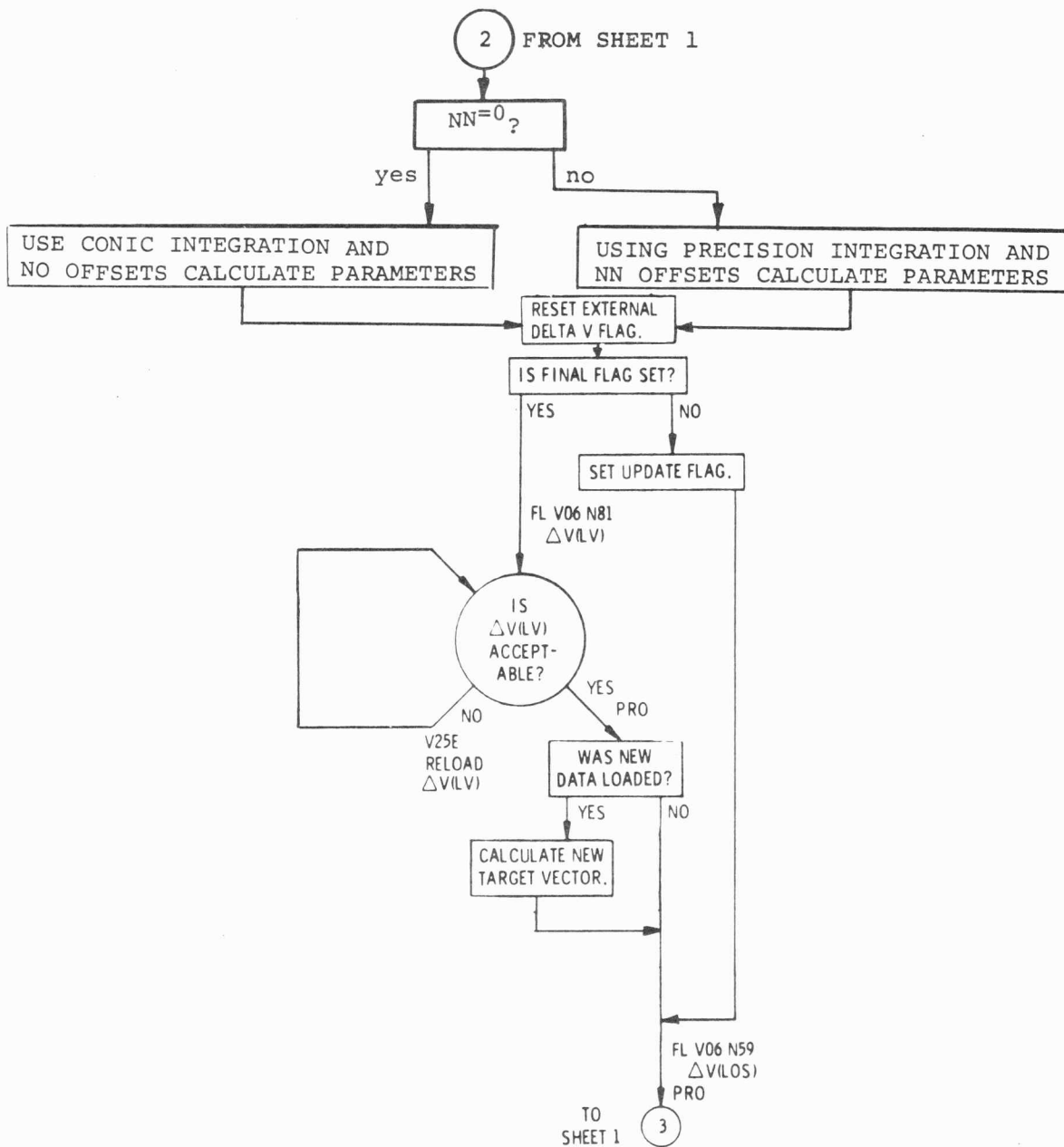


Figure 5.2.5-1. Transfer Phase Midcourse Program (P35) (Sheet 2 of 2)

TABLE 5. 2. 5-I

P35 INPUT

Input	Identification	Input Source (no inputs are displayed)	Comments
1*	Time of midcourse correction	TIG (TPM) is the time when the current recycle or final computation was requested, plus a pad-loaded or up-linked delay interval, A. A is usually about three minutes.	Given that t_{IG} (TPM) changes with each recycle or final computation (or restart, if one occurs between the request for a recycle or final computation and the corresponding solution), one can expect the calculated maneuver to change somewhat with each computation.
2*	Time of intercept	Calculated by P34 from CENTANG.	
3*	Conic-Precision offset target switch, NN.	If P34 was requested to do conic targeting (R1 of NOUN 55 = 00000), P35 will do the same. If P34 did a certain number of precision offsets, P35 will do the same number.	

* No actual input is required.

TABLE 5.2.5-II

P35 OUTPUT (SHEET 1 OF 2)

Input	Identification	Mnemonic	DSKY	Register	Comments
1	VHF and optics marks incorporated since latest significant event in P20 (i. e., P20 originally selected, W-matrix reinitialized, AVERAGEG or P76 terminated.)	Mark counters	FL V16 N45	R1 xxBxx	A VERB 32 ENTR response to a flashing VERB 16 NOUN 45 display will recycle for a preliminary computation. An initial PRO response will halt incorporation of marks and allow final computation. If it is decided that the final computation cannot be used, a VERB 32 ENTR response will allow a final comp with a slightly later $t_{IG}(TPM)$. Once an initial PRO has been keyed in response to a flashing VERB 16 NOUN 45 display, no more marks will be incorporated until UPDATE flag is once again set--for instance by re-selecting P35.
2	Time from ignition	TFI	FL V16 N45	R2 xxBxx min, sec	
3	Final computation; recycle indicator. Middle gimbal angle at $t_{IG}(TPM)$	Middle gimbal angle	FL V16 N45	R3 xxx.xx deg	If displayed value = -00001, PRO has not been keyed in response to a VERB 16 NOUN 45 flashing display. If PRO has been keyed in response to that display, then a positive number indicates the MGA at $t_{IG}(TPM)$. -00002 indicates IMU alignment is not currently known.
4	Impulsive change in velocity, in Local Vertical Coordinates.	DELTA V(LV)	FL V06 N81	R1 xxxx.x fps X R2 xxxx.x fps Y R3 xxxx.x fps Z	Flashed only after final computation. The Y component may be overwritten with $-Y(CSM)$, calculated by R36 with $T(EVENT) = t_{IG}(TPM)$.

TABLE 5.2.5-II
P35 OUTPUT (SHEET 2 OF 2)

Input	Identification	Mnemonic	DSKY	Register	Comments
5	Impulsive change in velocity vector, in LOS coordinates.	DELTA V(LOS)	FL V06 N59	R1 xxxx. x fps X R2 xxxx. x fps Y R3 xxxx. x fps Z	LOS coordinates are defined in paragraph 5.2.4.

maneuver be recalculated about 12 minutes later in the lunar sphere, to eliminate the loss of any out-of-plane correction. A delay allows the transfer angle to become less than 165 deg.

5.2.5.4 Restarts

If a restart occurs during the calculation of the TPM maneuver (after a response to VERB 16 NOUN 45 but before the next display), P35 starts again just after the VERB 16 NOUN 45 display. Since A, the time increment (refer to 5.2.5 c), is added to the current time after the restart protection point in the program, the maneuver will be targeted for a time slightly later than A plus the time of restart occurrence.

5.2.6 P37, Return-to-earth Targeting

Program P37 provides the crew with an onboard means of targeting for a Lambert-aimpoint maneuver that will return the spacecraft to a proper earth-reentry state.* Targeting with P37 is wholly independent of earth communication and can be used either for an SPS maneuver (P40) or an RCS maneuver (P41).** The program can be utilized to return from (a) earth orbit, (b) trajectories resulting from translunar-injection powered-maneuver failure, (c) translunar coast (outside lunar sphere of influence), and (d) transearth coast, including midcourse corrections (again, outside lunar sphere of influence). (See Figures 5.2.6-1, -2, and -3.)

5.2.6.1 Options and Crew Inputs

P37 has three basic options—minimum fuel, minimum time, and adjusted landing site. For either of the three, the crew enters five inputs via the DSKY and receives fifteen outputs. (See Table 5.2.6-I, and refer to program flow, Figure 5.2.6-4.) The first six outputs present a relatively fast, conic-section solution; the second six (outputs 7-12) present the precision-solution equivalent of the first six, recomputed to consider gravitational perturbations. After keying in VERB 37 ENTR 37 ENTR, the crew enters the first three inputs as requested by the DSKY—desired ignition time (t_{IG}), desired velocity change (Δv_D), and desired reentry angle $\{\gamma(t_2)_D$. Whether it is to be a minimum-fuel or a minimum-time return is determined by the input Δv_D . Whether it is to be an adjusted-landing-site return is determined by crew decision to vary certain of the inputs in order to effect a desired change in landing-site longitude.

5.2.6.1.1 Minimum-fuel Option.—For a minimum-fuel return, the crew allows zero to remain in register 2 in response to the DSKY's flashing VERB 06 NOUN 60. A Δv_D of zero signals the program to compute a trajectory requiring the minimum possible velocity change. In addition, from certain earth-orbital conditions (see Figure 5.2.6-5), the crew can further minimize fuel consumption by selecting a shallower entry flight-path angle than would be otherwise automatically computed by the program. That is, in response to VERB 06 NOUN 60, the crew can leave a

* See appropriate GSOP: Section 4, "GNCS Operational Modes," and Section 5 (paragraph 5.4.3), "Guidance Equations."

** See paragraph 5.2.6.8 for a special application of P37 outputs to returns using the lunar-module propulsion system.

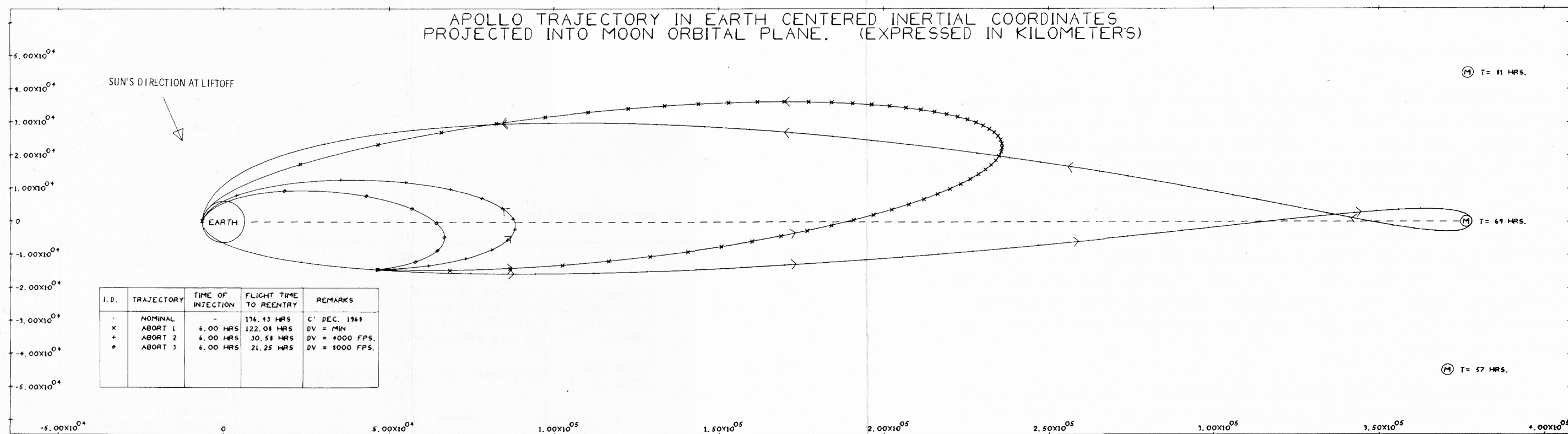


Figure 5.2.6-1. Typical Abort Trajectories for TLI +6 Hours

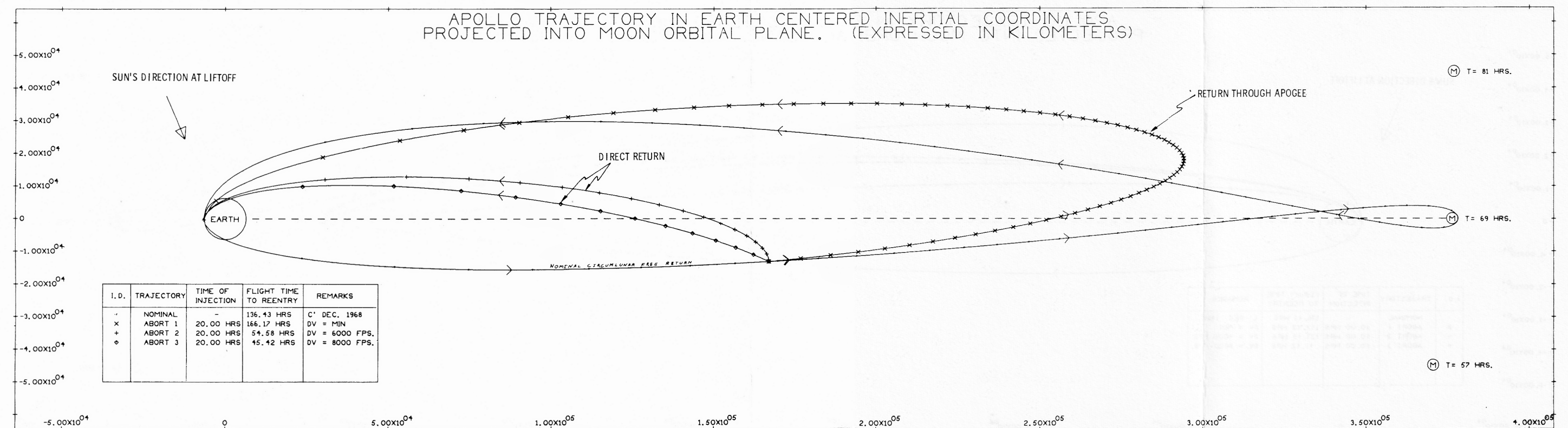


Figure 5.2.6-2. Typical Abort Trajectories for TLI +20 Hours

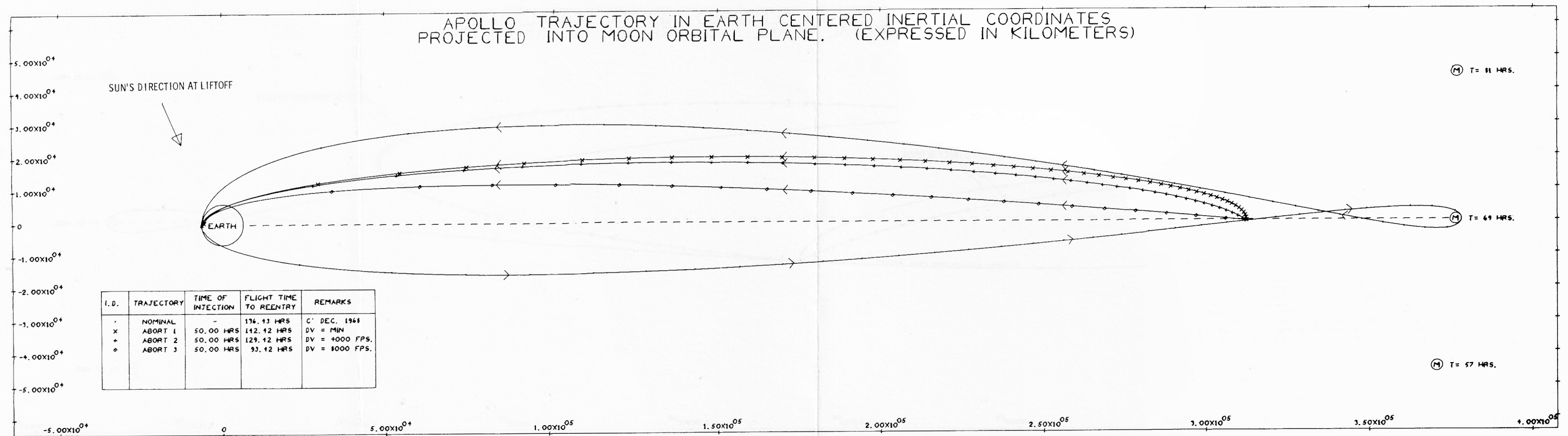


Figure 5.2.6-3. Typical Abort Trajectories for TLI +50 Hours

TABLE 5.2.6-1

P37 CREW INPUTS AND PROGRAM OUTPUTS (SHEET 1 OF 2)

Input	Identification	Display Mnemonic	DSKY	Register
1.	Desired Ignition Time (t_{IG})	TIG (GET I)	FL V06 N33	R1 <u>ooxxx.</u> hr R2 <u>ooxxx.</u> min R3 <u>oxx.xx</u> sec
2.	Desired Velocity Change (Δv_D)	VPRED	FL V06 N60	R2 <u>xxxxx.</u> fps
3.	Desired Reentry Angle [$\gamma(t_2)_D$]	GAMMA EI	FL V06 N60	R3 <u>xxx.xx</u> deg*
4.	Vehicle Mass and Number of Jets**			
5.	Desired Propulsion System	SPS RCS	FL V04 N06	R2 <u>00001</u> (R1 <u>00007</u>) R2 <u>00002</u> (R1 <u>00007</u>)
Output				
1.	Landing-site Latitude (θ_{LAT})	IMPACT LAT	FL V06 N61	R1 <u>xxx.xx</u> deg*
2.	Landing-site Longitude (θ_{LONG})	IMPACT LONG	FL V06 N61	R2 <u>xxx.xx</u> deg*
3.	Time of Flight ($t_2 - t_1$, or t_{21})	DELTA T TRANS	FL V06 N39	R1 <u>ooxxx.</u> hr R2 <u>ooxxx.</u> min R3 <u>oxx.xx</u> sec
4.	Velocity at Entry [$v(t_2)$]	VPRED	FL V06 N60	R2 <u>xxxxx.</u> fps
5.	Entry Flight-path Angle [$\gamma(t_2)$]	GAMMA EI	FL V06 N60	R3 <u>oxx.xx</u> deg*
6.	Impulsive Velocity Change ($\Delta \underline{v}$)	DELTA V (LV)	FL V06 N81#	R1 (VX) <u>xxxx.x</u> fps*** R2 (VY) <u>xxxx.x</u> fps*** R3 (VZ) <u>xxxx.x</u> fps***
7-12.	Outputs 1-6 recomputed, giving precision solution			
13.	Ignition Time (t_{IG})	TIG (GET I)	FL V06 N33	R1 <u>ooxxx.</u> hr R2 <u>ooxxx.</u> min R3 <u>oxx.xx</u> sec

zero $\nu(t_2)_D$ in R3, allowing the program to solve for a flight-path angle obtaining the center of the entry corridor; or by keying into R3 a specified entry angle, the crew can request the program to solve for a shallower $\nu(t_2)$, requiring less fuel. For example, observe in Figure 5.2.6-5 that at an orbital altitude of 140 n. mi. a change in ν from -3 deg to -2 deg reduces the required Δv by approximately 450 ft/sec.

TABLE 5.2.6-I

P37 CREW INPUTS AND PROGRAM OUTPUTS (SHEET 2 OF 2)

Output	Identification	Display Mnemonic	DSKY	Register
14.	Time from Ignition	TFI (TF GET I)	FL V16 N45	R2 <u>xxBxx</u> min, sec*
15.	Middle-gimbal Angle at Ignition (a_{MG})	MGA	FL V16 N45	R3 <u>oxx.xx</u> deg*

*Sign convention;

$\nu--"--$ designates below horizontal plane

$\theta--"--$ designates north latitude, east longitude

$a_{MG}--"--$ indicates IMU not aligned

TFI--"-- indicates before t_{IG} ; "+" after t_{IG} .

**Mass data are not specifically requested by the program—must be loaded via Routine 03 before program is allowed to proceed beyond input 5.

***VX is component of impulsive Δv , at t_{IG} , along $(\underline{RXV})\underline{XR}$

VY is component of impulsive Δv , at t_{IG} , along \underline{VXR}

VZ is component of impulsive Δv , at t_{IG} , along $-\underline{R}$.

Where \underline{R} is CSM geocentric radius vector, and \underline{V} is inertial-velocity vector at t_{IG} .

The scalar Δv can be observed here by keying VERB 06 NOUN 40 (R2 xxxx.xfps).

NOTE: Offset-target data relative to the Lambert-aimpoint maneuver are not displayed, but are transferred to the appropriate erasables for the applicable powered-flight guidance program.

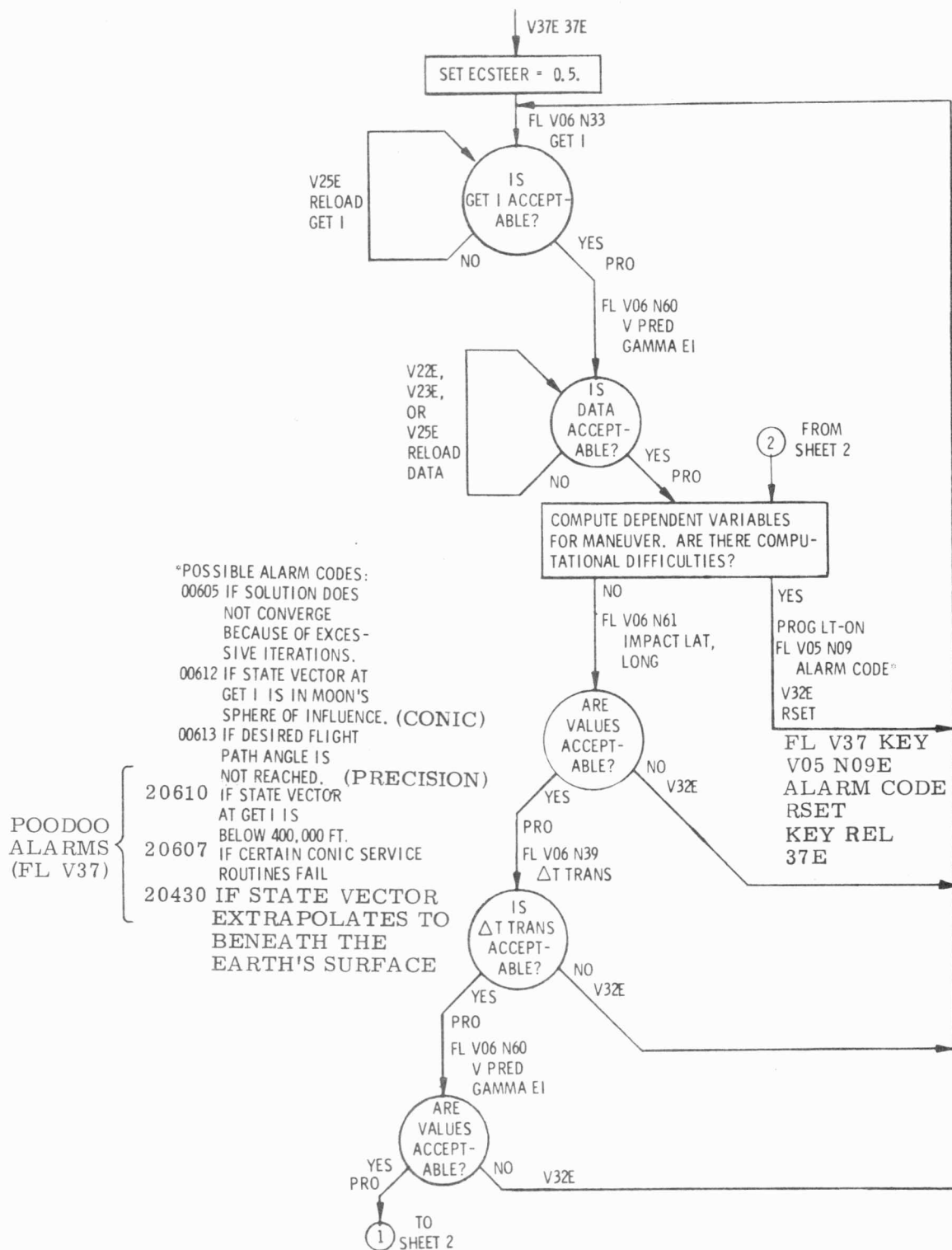


Figure 5.2.6-4. Return to Earth Program (P37) (Sheet 1 of 2)

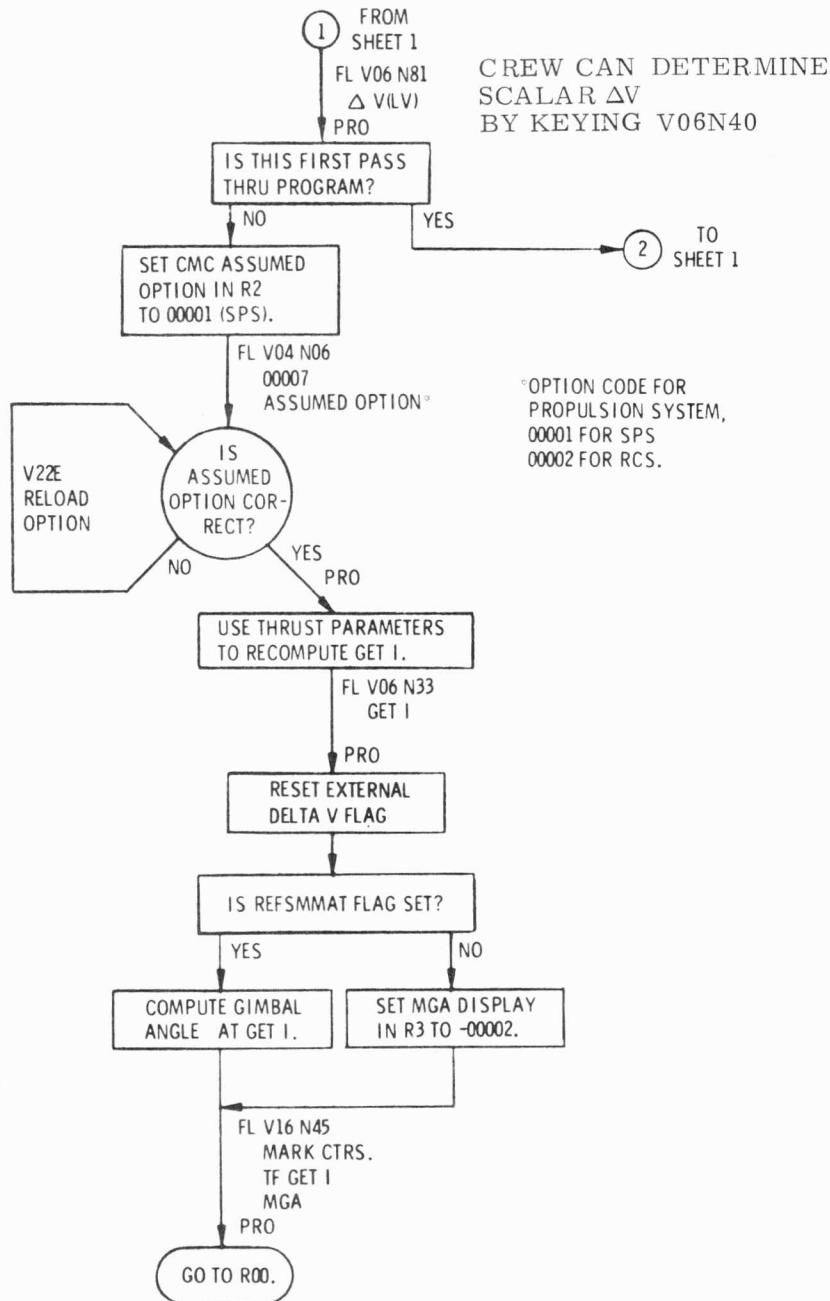


Figure 5.2.6-4. Return To Earth Program (P37) (Sheet 2 of 2)

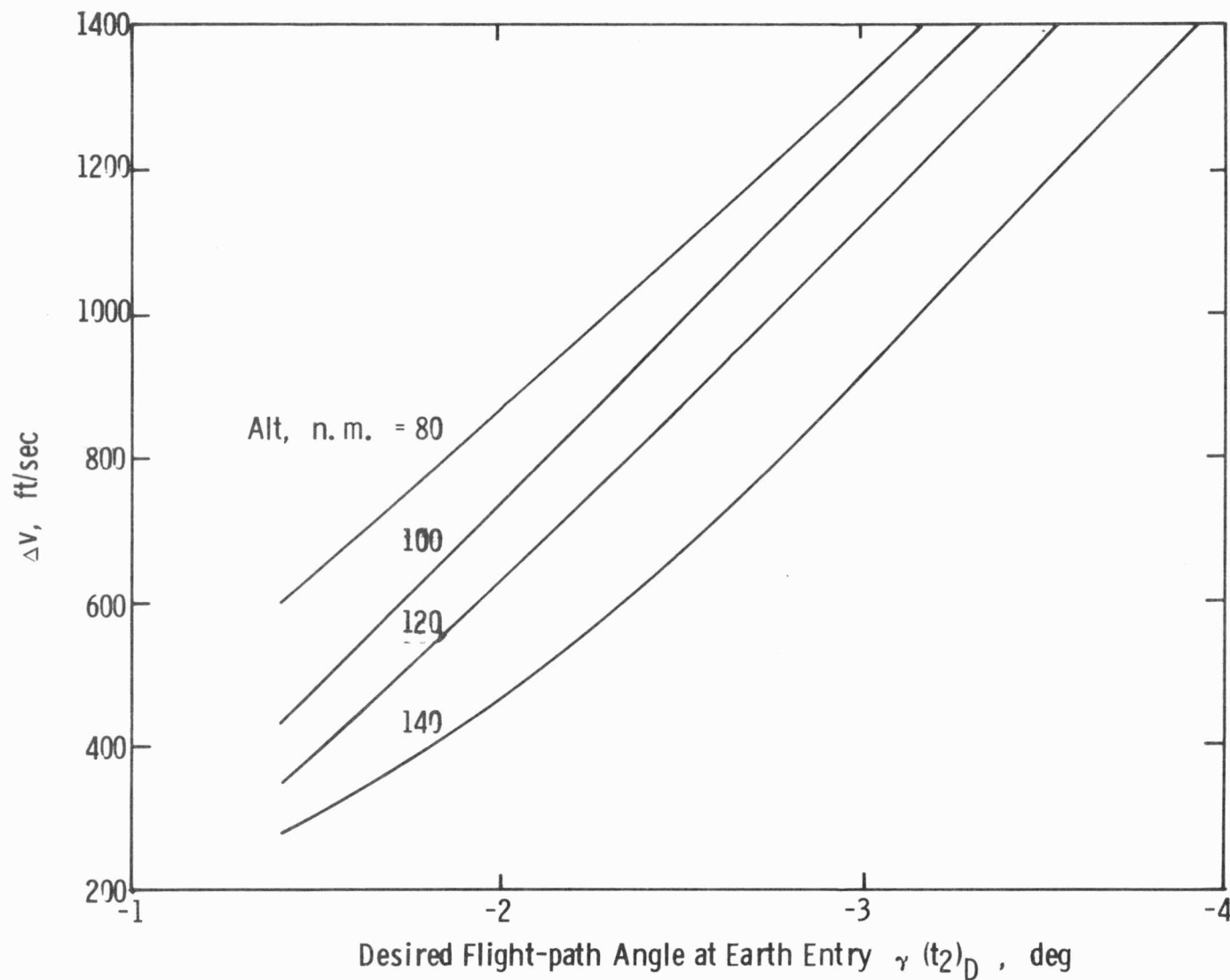


Figure 5.2.6-5. Relationship of Δv to Desired Flight-path Angle at Earth Entry: Returns from Near-circular Earth Orbits of Several Altitudes

Normally, minimum-fuel maneuvers executed during transearth coast have only an x-component (local vertical coordinates). Should the pre-maneuver state vector have a value, however, that would result in a velocity at entry $[v(t_2)]$ greater than $38,000 \pm 5$ fps, the program will automatically compensate for the excess velocity and produce a Δv output having both an x- and a negative z-component, i.e., a decelerating effect.

Another factor for consideration is the possibility that the minimum-fuel solution will specify a Δv that exceeds the fuel-onboard capability. Should this occur during translunar coast, the solution to the problem might be to utilize the free-return feature of the TLI trajectory and to use P37 for midcourse corrections on the way back to earth. (Figure 5.2.6-6 shows the minimum Δv required for a return from various translunar-coast distances.) During transearth coast, the minimum Δv required to adjust the entry angle increases as range decreases. Therefore, a P37 targeted maneuver should be executed as early as possible after exiting the lunar sphere of influence.

5.2.6.1.2 Minimum-Time Return.—For a minimum-time return, the crew keys into register 2 the maximum Δv obtainable with the fuel on-board. Should the Δv input be less than required for a minimum-fuel return, the program will respond as though a zero Δv_D has been entered and will compute a minimum-fuel return. Should the Δv_D input exceed P37-imposed limits, the program will automatically compute a trajectory for the maximum-allowable Δv . For example, should the Δv_D result in a $v(t_2)$ greater than $38,000 \pm 5$ fps, the program would automatically limit the Δv to a value resulting in a $v(t_2)$ equal to $38,000 \pm 5$ fps. As with a minimum-fuel return, a pre-maneuver state vector that would result in a $v(t_2)$ greater than $38,000 \pm 5$ fps will be corrected by a Δv output having both an x-component and a negative z-component. This has ramifications regarding landing-site selection and will be discussed further under that subject.

5.2.6.1.3 Adjusted-landing-site Return.—In addition to the basic options of a minimum-fuel or a minimum-time return, the crew has a limited capability of varying landing site. The salient characteristics of the capability are as follows:

- a) Landing-site values ($\theta_{LAT}, \theta_{LONG}$) can either be approximations based on the AUGKUGL routine (GSOP Section 5, paragraph 5.6.10.2), which determines time and range from entry to landing for a half-lift entry trajectory, or they can be computed using a padloaded value for entry range. (Time, however, would still be based on AUGKUGL range.) The method used will be determined by the value entered in P37RANGE.

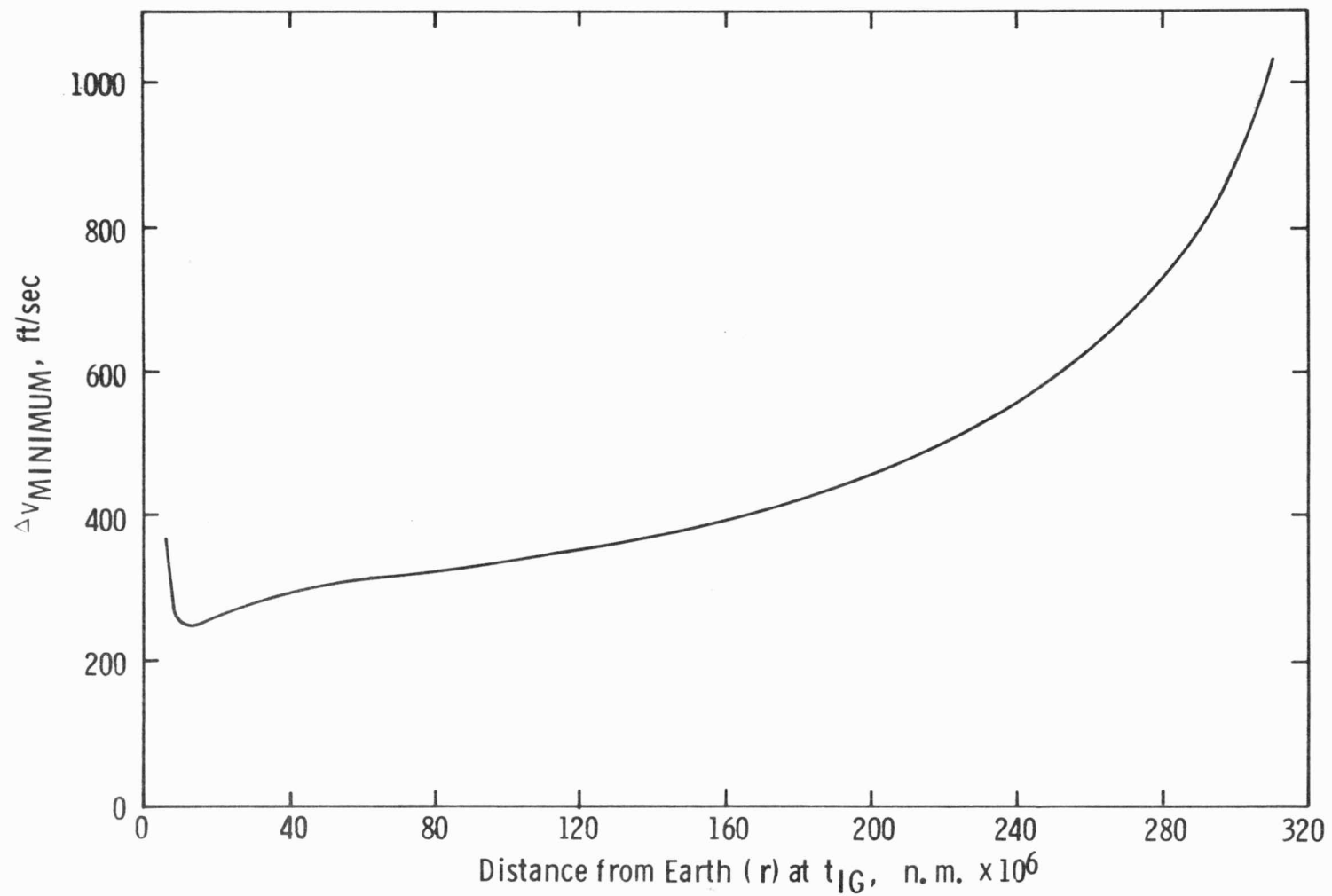


Figure 5.2.6-6 Minimum Fuel Requirements During Translunar Coast

(Table 5.2.6-II gives typical ranges and their octal equivalent. The exact octal value for any range can be computed by converting to octal the product, range times 0.758.) A zero in P37RANGE signals P37 to use AUGEKUGL to compute entry range; a specific value entered in P37RANGE signals P37 to use that value as the entry range. (Figure 5.2.6-7 illustrates AUGEKUGL entry range as a function of entry angle and velocity.)

- b) The crew input most effective in varying the landing site when in earth orbit is the desired ignition time (t_{IG}), that most effective when in translunar or transearth coast is the desired velocity change (Δv_D). (See Figure 5.2.6-8.)
- c) From earth orbit, landing-site adjustment is constrained by the minimum t_{21} required for completing pre-entry procedures. For example, during the apogee-to-perigee phase of the orbit (negative flight-path angle), the magnitude of t_{21} is approximately 3-1/2 minutes, which is insufficient for preparing the spacecraft for reentry; during the perigee-to-apogee phase, however, the magnitude of t_{21} is approximately 25 minutes. Therefore, we recommend that, normally, a t_{IG} be selected that will occur during the perigee-to-apogee phase. Should this prove impractical—because of landing site—the crew can extend t_{21} somewhat by selecting a shallower entry angle. (See Figure 5.2.6-9.)

TABLE 5.2.6-II

ENTRY RANGE AND OCTAL EQUIVALENT LOADED IN P37RANGE

(LOADED BY VERB 21 NOUN 01 ENTR, 3376 ENTR, xxxxx ENTR)

Range, n.mi.	Octal Equivalent
1200	01616
1250	01664
1300	01732
1350	02000
1400	02046
1450	02114
1500	02162
1550	02230
1600	02276
1650	02344
1700	02411
1750	02457
1800	02525

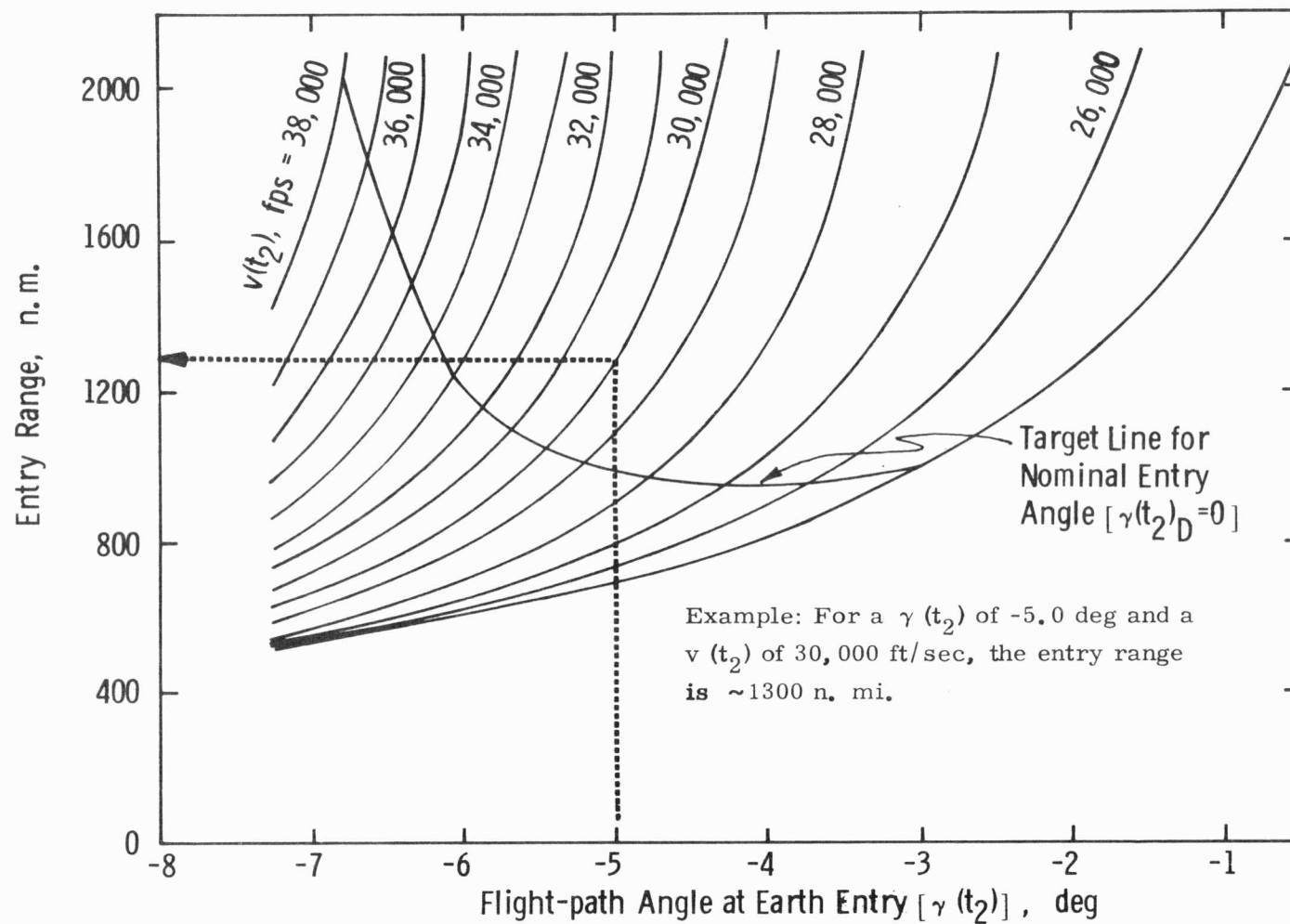
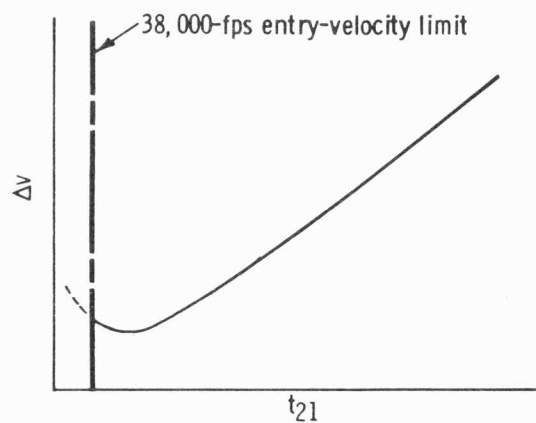
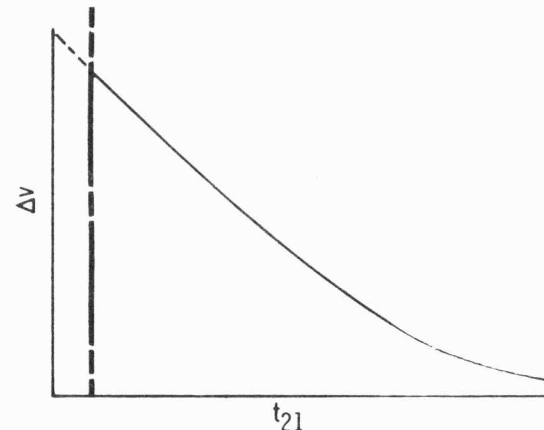


Figure 5.2.6-7. Range from Entry Interface (400,000 ft) to Landing



(a) Transearth Coast



(b) Translunar Coast

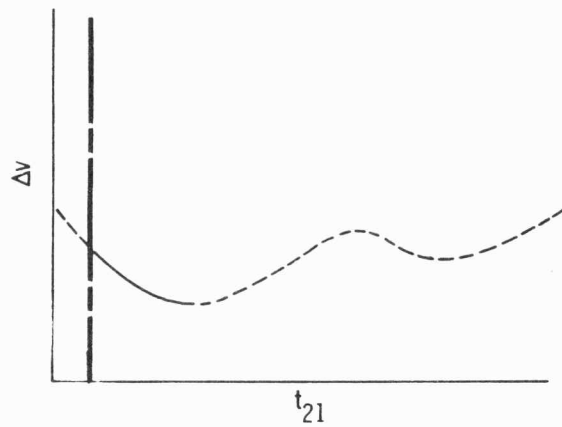
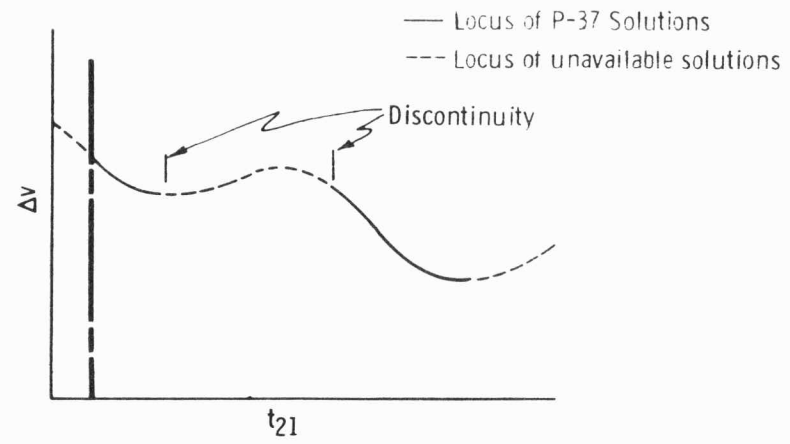
(c) Apogee-to-perigee Earth Orbit
and Near-in Transearth Coast(d) Perigee-to-apogee Earth Orbit
and Near-in Translunar Coast

Figure 5.2.6-8. Locus of Available Solutions for Four Typical Pre-maneuver State Vectors

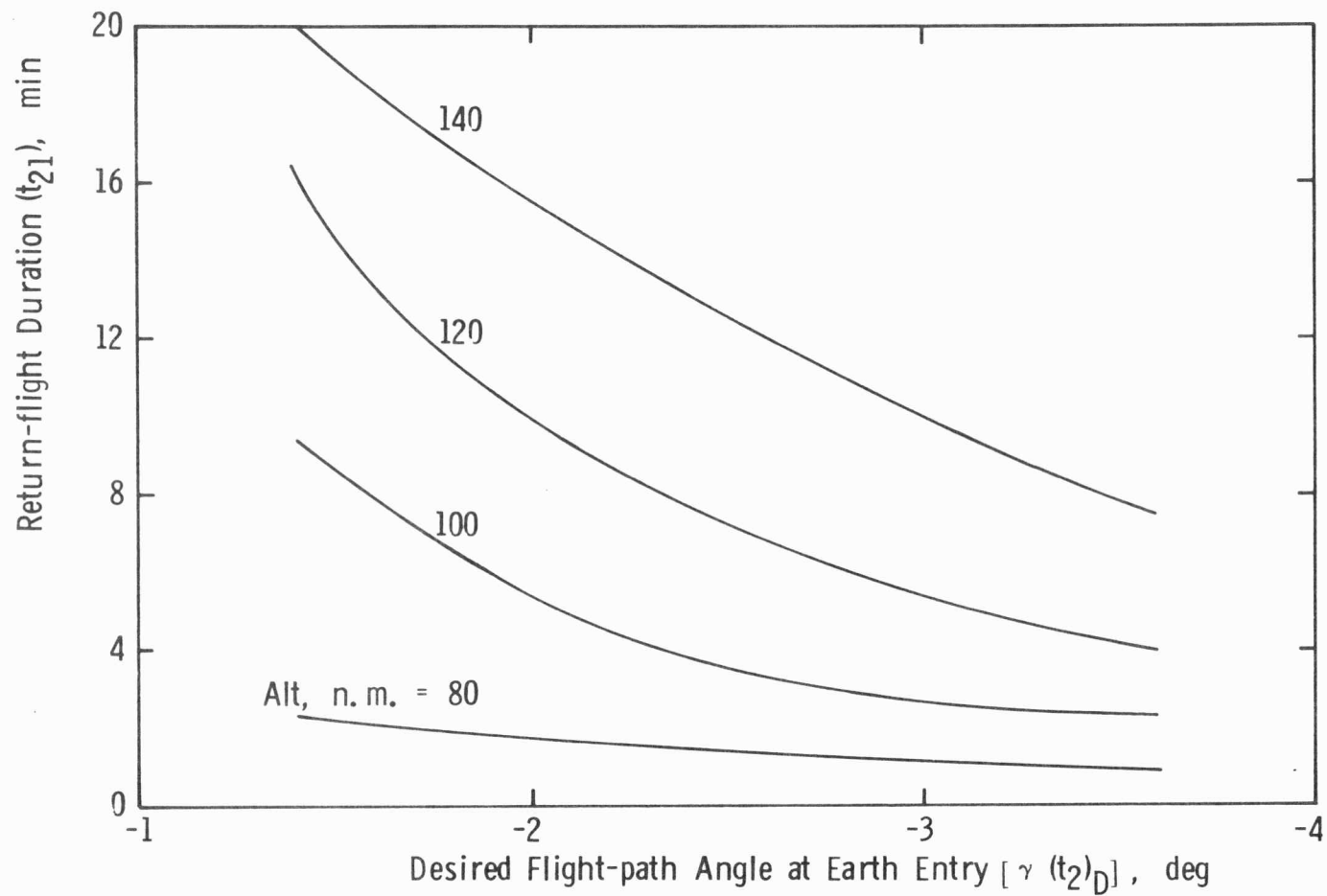


Figure 5.2.6-9. Relationship of Return-flight Duration to Desired Flight-path Angle at Earth Entry: Returns from Near-circular Earth Orbits of Several Altitudes (with Negative Pre-maneuver Flight-path Angles)

- d) When return-flight durations (t_{21}) are large, i.e., several days, the precision solution may vary significantly from the conic solution. (See Figure 5.2.6-10.) The procedure recommended in that situation, for determining (1) the sensitivity of landing-site longitude to changes in Δv_D and, thus (2), the required change in Δv_D for effecting the desired adjustment in landing site, will be explained in paragraph 5.2.6.4.

5.2.6.3 Program Outputs and Computation Sequence

Regardless of option, the program computes, first, a conic solution and, second, a precision solution. (Refer to Figure 5.2.6-4.) The conic, two-body solution displays a relatively fast approximation of the return-to-earth targeting information. In arriving at the conic solution, P37 first must extrapolate the existing state vector up to the input t_{IG} . This may take several minutes, depending upon t_{IG} . Once the state-vector has been extrapolated, the conic solution obtains within seconds. The crew can either accept the conic-solution approximations and continue with the precision solution, or the crew can vary the inputs and reiterate, as many times as necessary, for a new set of conic approximations. Except for situations that will be discussed, the conic-solution values will be sufficiently accurate for the crew to determine whether the final (precision) solution will be acceptable. The precision solution may require as little as 2 minutes and as much as 35 minutes—depending upon the trajectory. (See Figure 5.2.6-11.)

5.2.6.3.1 Program Output.—Table 5.2.6-I presents the 15 outputs displayed to the crew. The first six are the dependent variables displayed after the conic solution; the second six (outputs 7–12) are the first six recomputed, giving the precision solution. The latter are followed by a display of the burn data (outputs 13–15).

The dependent variables (outputs 1–12) are determined by crew inputs 1–3 as follows:

1. Landing-site latitude (θ_{LAT}) variability is small and only secondarily dependent upon input variables. (See in-plane-only limitation, paragraph 5.2.6.6.)
2. Landing-site longitude (θ_{LONG}) is the primary dependent variable in landing-site adjustment (paragraph 5.2.6.4).

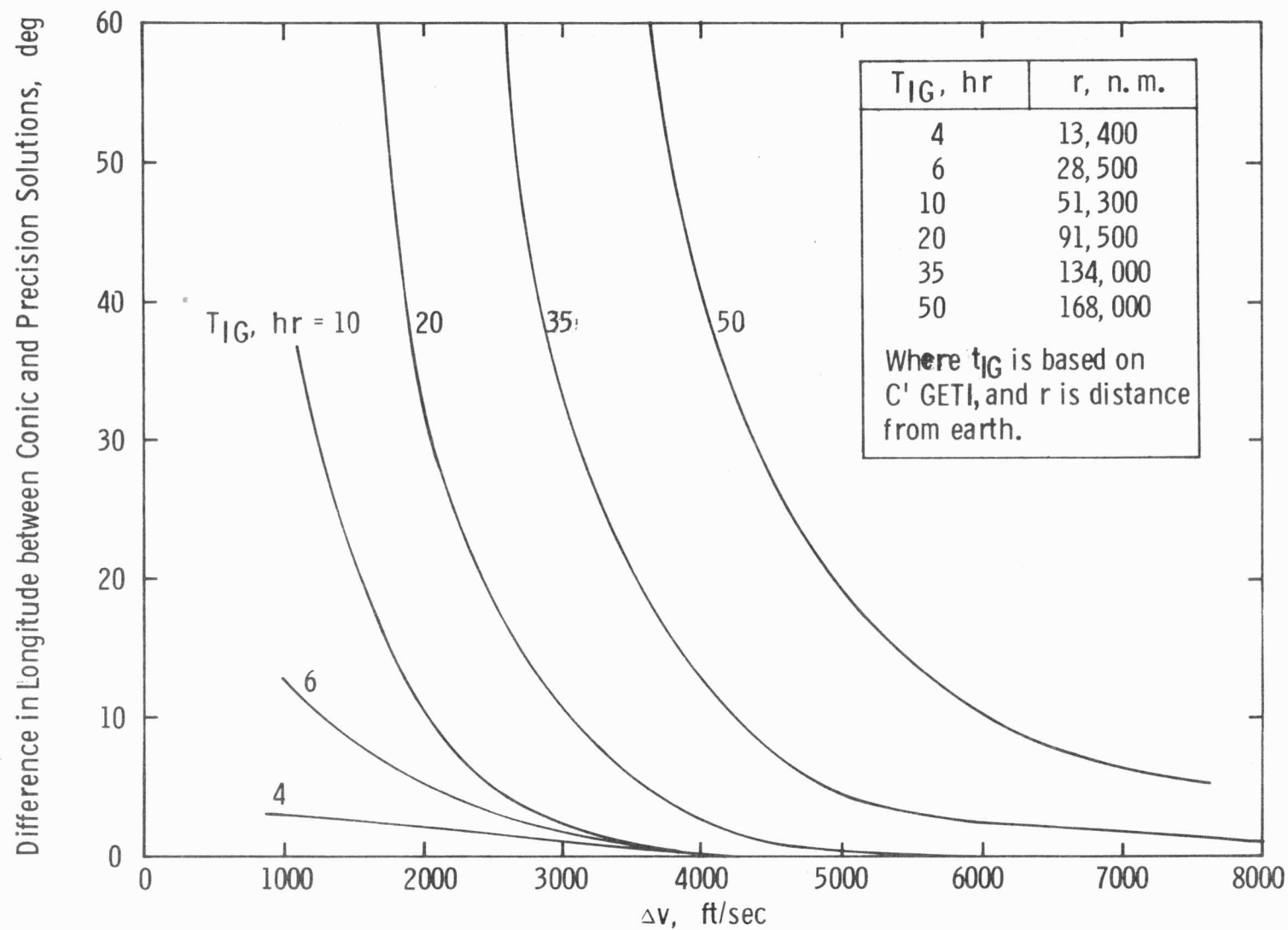


Figure 5.2.6-10. Correlation of Conic and Precision Solutions for Longitude: Returns from Translunar Coast

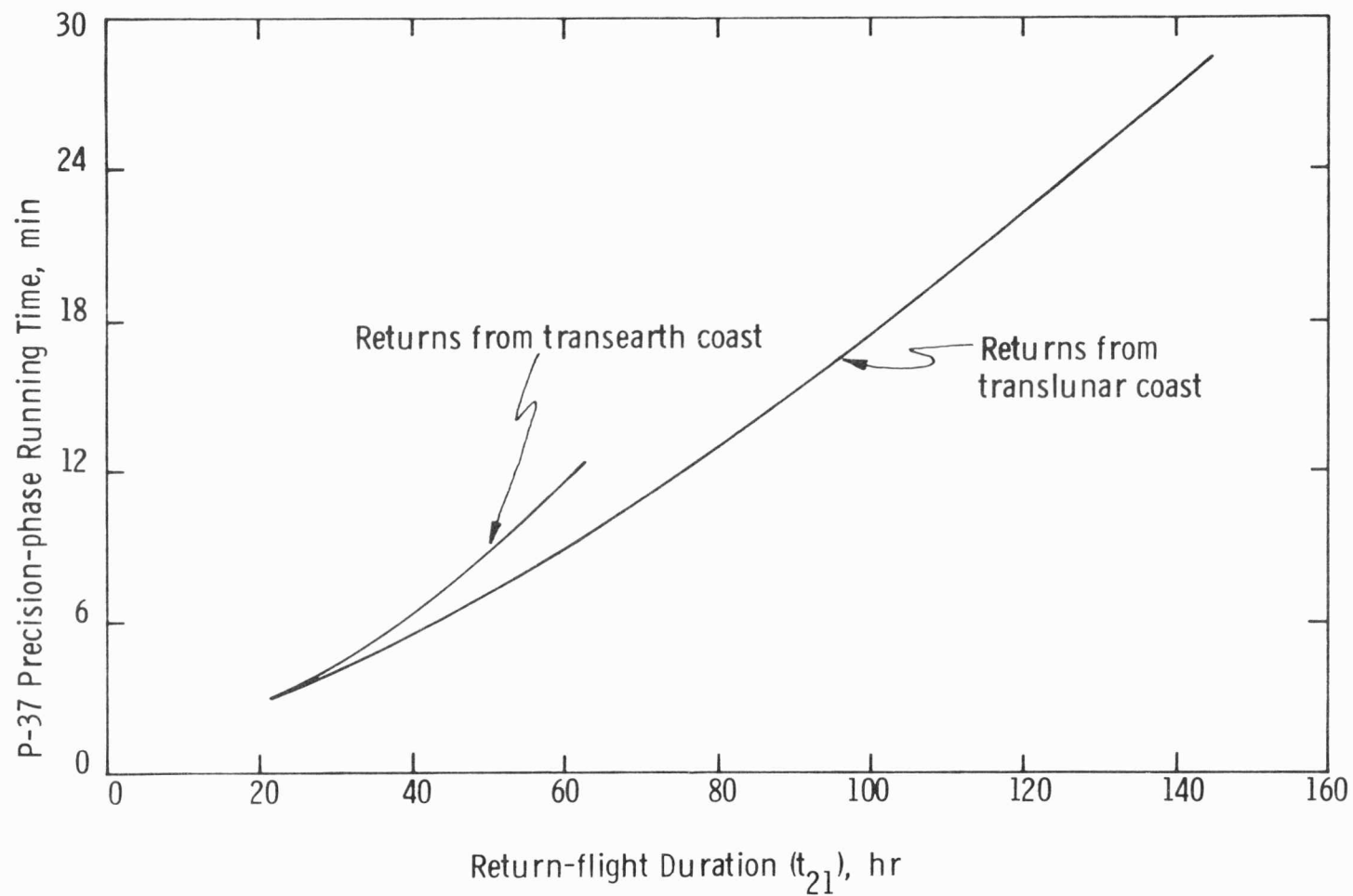


Figure 5.2.6-11. Approximate Relationship of Precision-phase Running Time versus Return-flight Duration

3. Time-of-flight (t_{21}) relative to Δv_D is illustrated for various pre-maneuver distances in Figure 5.2.6-12. Note that for minimum-fuel returns from the early part of an earth-outbound trajectory, the magnitude of t_{21} may be as much as five days for a return-through-apogee solution, but can be much less for a direct-return solution. See special case when t_{21} may be too short when entering from earth orbit—paragraph 5.2.6.1.3(c).

For a very long t_{21} , there will be a substantial difference in the conic and precision solutions. Although rarely occurring and no cause for alarm, a large difference in conic and precision t_{21} values does introduce a special case when reiterating for landing-site adjustment—discussed in paragraph 5.2.6.4.

4. Inertial velocity at entry [$v(t_2)$] is program limited within acceptable velocities for a corresponding entry flight-path angle. As a variable, the value of $v(t_2)$ is dependent upon the input Δv_D . Should the crew request a velocity change that will result in an entry velocity exceeding the maximum allowable, the program will adjust the input Δv_D downward to ensure an output $v(t_2)$ that is within the prescribed limits. [Note that both the input scalar Δv_D and the output scalar $v(t_2)$ use the VPRED register (NOUN 60); the Δv_D value, can be observed, however, in VERB 06 NOUN 56 ENTR, register 2.]
5. Entry flight-path angle [$\gamma(t_2)$] is determined by the input $\gamma(t_2)_D$. An input of zero will cause the program to automatically compute a $\gamma(t_2)$ appropriate for the computed $v(t_2)$. An input other than zero will cause the program to compute a trajectory obtaining the specifically requested entry angle. It should be noted, however, that when a value other than zero is entered, there is no assurance that the resulting trajectory will obtain the entry corridor.
6. Impulsive velocity change ($\Delta \underline{v}$) is determined by the input Δv_D and is the last of the dependent variables, displayed both after the conic and the precision solutions. The display is in local vertical coordinates whose y-component is always zero. (See in-plane-only restriction, paragraph 5.2.6.6.)

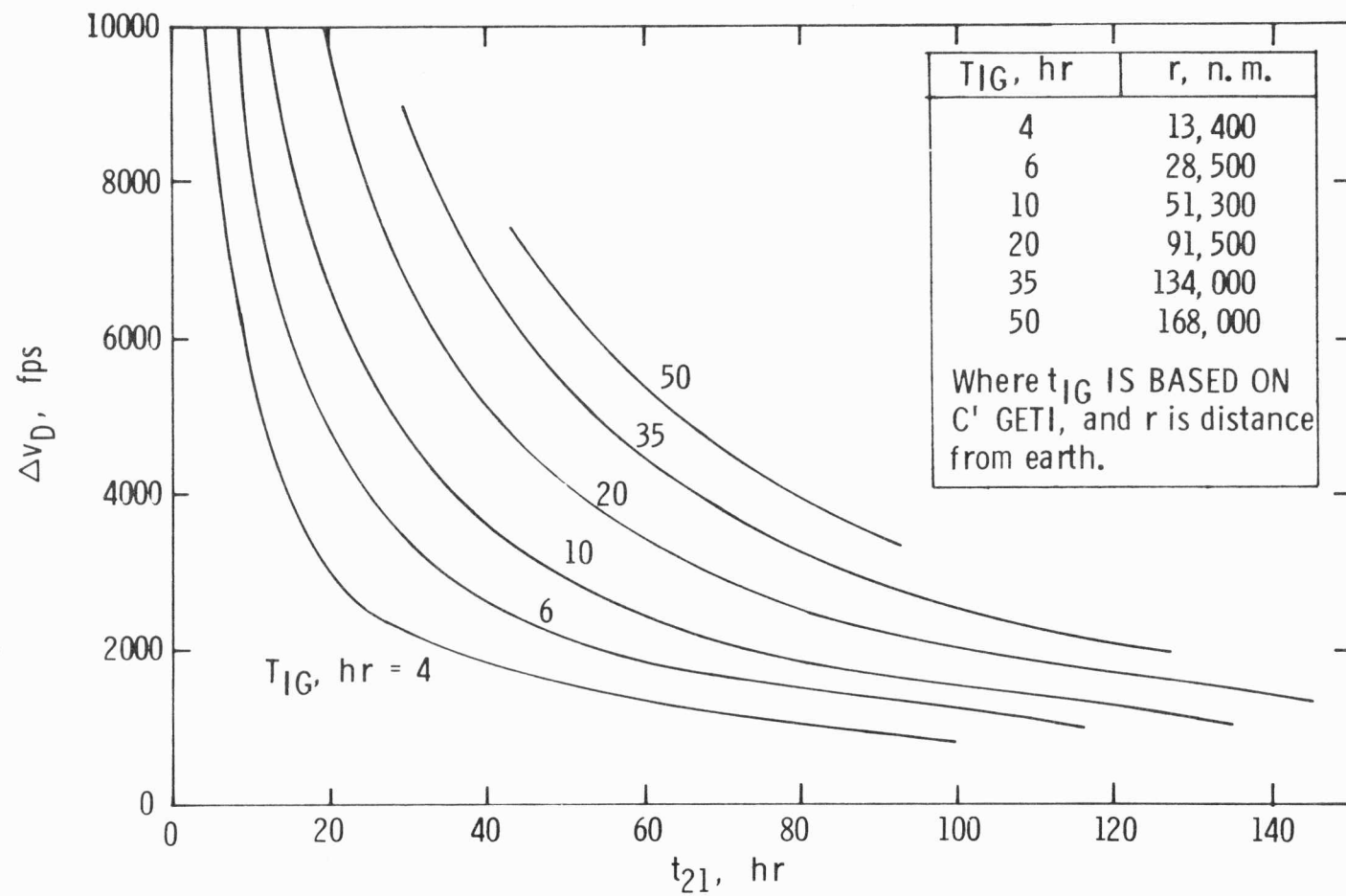


Figure 5.2.6-12. Relationship of Δv_D to Time of Flight (t_{21}) During Translunar Coast

The burn data (outputs 13-15) are displayed only after the precision solution is completed and the propulsion system has been selected: The precision time of ignition (t_{IG}) is presented to the nearest centisecond (ground elapsed time); time from ignition (TFI) is presented in minutes and seconds (maximum reading of ± 59 min 59 sec); and the middle-gimbal angle (a_{MG}) at ignition is presented to the nearest 0.01 deg. Note that the output t_{IG} will not be exactly the same as the input t_{IG} since the output value is adjusted for a finite thrusting duration calculated on the basis of the propulsion system selected and the mass of the vehicle. Note also that, although TFI overflow is 59 min 59 sec, this in itself implies no limitation on how long in advance of the desired maneuver time P37 can be called up. The actual TFI may, in fact, be considerably longer than the maximum indication. The limiting factor in this regard is the requirement that the state vector still be valid. (This requirement applies equally to the question of how many revolutions forward while in earth orbit the program can target an entry: subject to a valid state vector at t_{IG} , the crew can expect the targeting solution to be valid if P37 has proceeded to its conclusion without an alarm.) Finally, the crew should expect the sign value of the middle-gimbal-angle display to always be positive unless the IMU has not been aligned (REFSMMAT flag not set). If the IMU has not been aligned and a_{MG} (or MGA) cannot be computed, the value displayed will be -00002.

5.2.6.3.2 Computation Sequence.—Computation begins after the first three crew inputs into the DSKY. (Refer to Table 5.2.6-I and Figure 5.2.6-4.) Depressing the PRO key on the DSKY then signals the program to proceed with the computation of a conic-section solution, yielding the first six program outputs. By keying in VERB 16 NOUN 38, the crew has the option of monitoring the state-vector time as it extrapolates to t_{IG} . When the state vector reaches t_{IG} , the conic solution will follow within seconds. If NOUN 38 is being monitored, the DSKY will flash KEY REL.

After the conic solution has been accepted by the crew's depressing the PRO key (or reiterated by keying VERB 32 ENTR and loading new inputs), the program proceeds to recompute for a precision solution encompassing all gravitational perturbations. Outputs 7 through 12, corresponding to conic-solution outputs 1 through 6, are then displayed by the DSKY. Note that the elapsed computer time required by the precision solution is roughly proportional to the return-flight (t_{21}); e.g., for a return flight of 6 or 7 days, the precision computation time may be as much as 35 minutes; for a return from an earth orbit or from a near-in transearth trajectory, the computation time can be as little as 2 minutes. Again, by keying in VERB 16 NOUN 38, the crew can monitor the program as it converges to a solution. Normally, the state-vector time will advance from t_{IG} to the time of entry (t_2), "hunt" briefly in the vicinity of t_2 , then snap back to t_{IG} , repeating the cycle as

many as seven times as the program converges to a solution. Should the state-vector time advance significantly beyond t_2 or snap back to a time earlier than t_{IG} , the crew should suspect that the solution is not converging and that it will be necessary to change t_{IG} and reenter the program. (See "Additional Restrictions," paragraph 5.2.6.6.)

The crew must enter the mass data and select the number of RCS jets (input 4) by executing R03 anytime before proceeding beyond the selection of the desired propulsion system (input 5). After the conic and precision solutions have been computed, displayed, and approved, the DSKY will display (VERB 04 NOUN 06) the option code for the service propulsion system (00001 in R2), which is the CMC-assumed option. Should the crew wish to select the reaction-control-system (RCS) option, the operator would key in VERB 22 ENTR and load (in R2) option code 00002. Before depressing the PRO key, signaling the program to proceed with the computation of t_{IG} (output 13) is the last instance when valid mass data can be entered. This information, however, will not be specifically requested by the program, which will assume as valid the last data entered. Therefore, unless R03 had been executed earlier—and the data were still valid—the crew would now key in VERB 48 ENTR, complete R03, and then continue P37 (by depressing the PRO key). Receiving a PRO signal from the crew, the program will either compute the middle-gimbal angle at ignition (REFSMMAT flag set, IMU aligned) or indicate (-00002 in register 3) to the crew that a_{MG} cannot be computed (REFSMMAT flag not set). If computed, the middle-gimbal angle at ignition will itself be displayed in R3, and the time from ignition displayed in R2. The crew's depressing the PRO key signals P37 to proceed to completion.

5.2.6.4 Procedure for Adjusting Landing Site During Cislunar Coast

For an adjusted-landing-site return from translunar coast, the crew would initially enter the maximum Δv_D available with the fuel onboard—the same as for a minimum-time return. Should the resulting landing site be unacceptable, the crew would recycle the program, adjusting Δv_D input downward, until an acceptable landing site was obtained. To assist in determining the sensitivity of landing-site longitude to variations in Δv_D , the following procedure is recommended—refer to Figures 5.2.6-13 and -14:

1. Reiterate (using Figure 5.2.6-13) the conic solution until it obtains a landing-site longitude ($\theta_{LONG_{C_1}}$) within 15 deg of desired (θ_{LONG_D}).

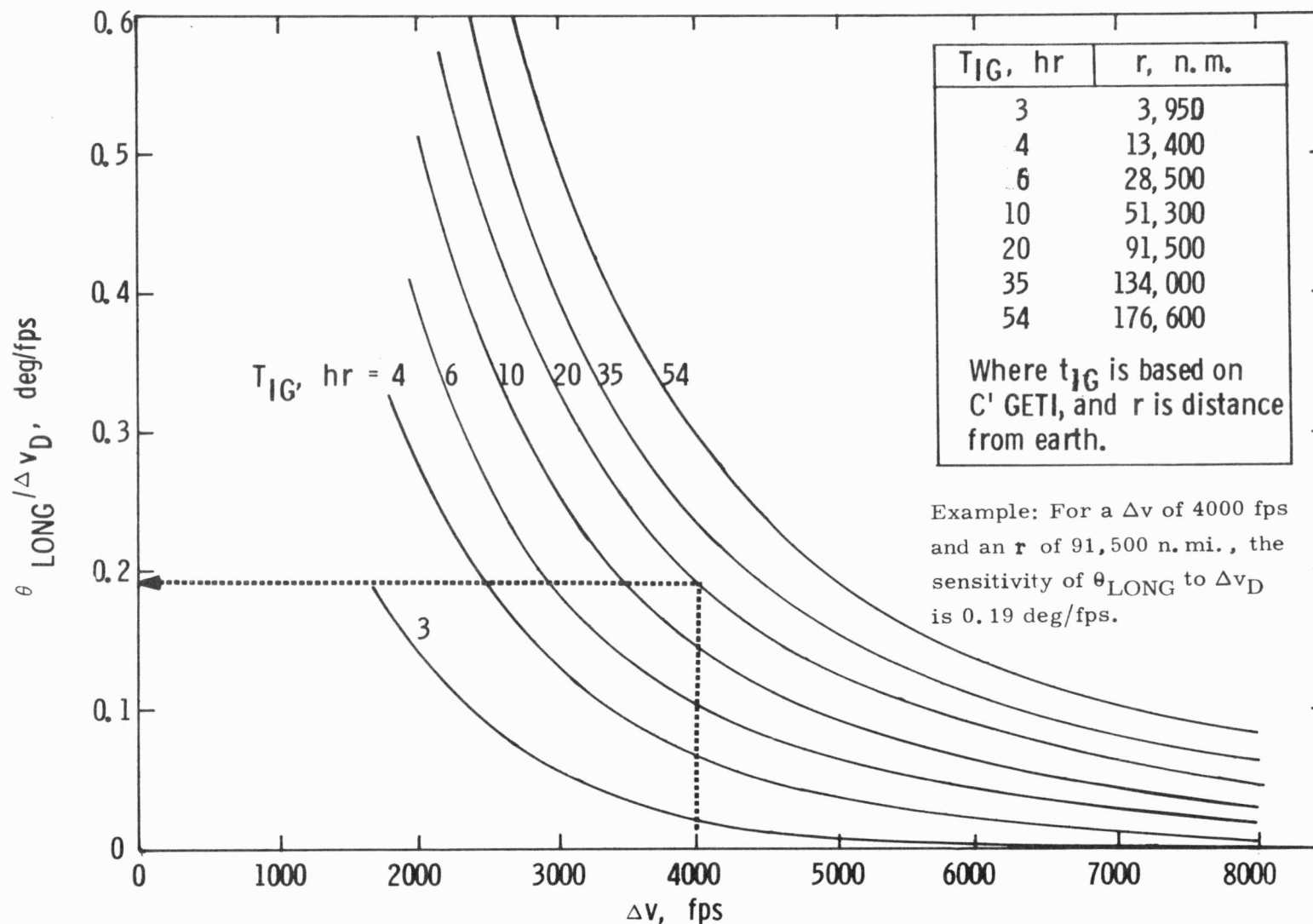


Figure 5.2.6-13. Sensitivity of Landing-site Longitude to Changes in Δv_D : Returns from Translunar Coast

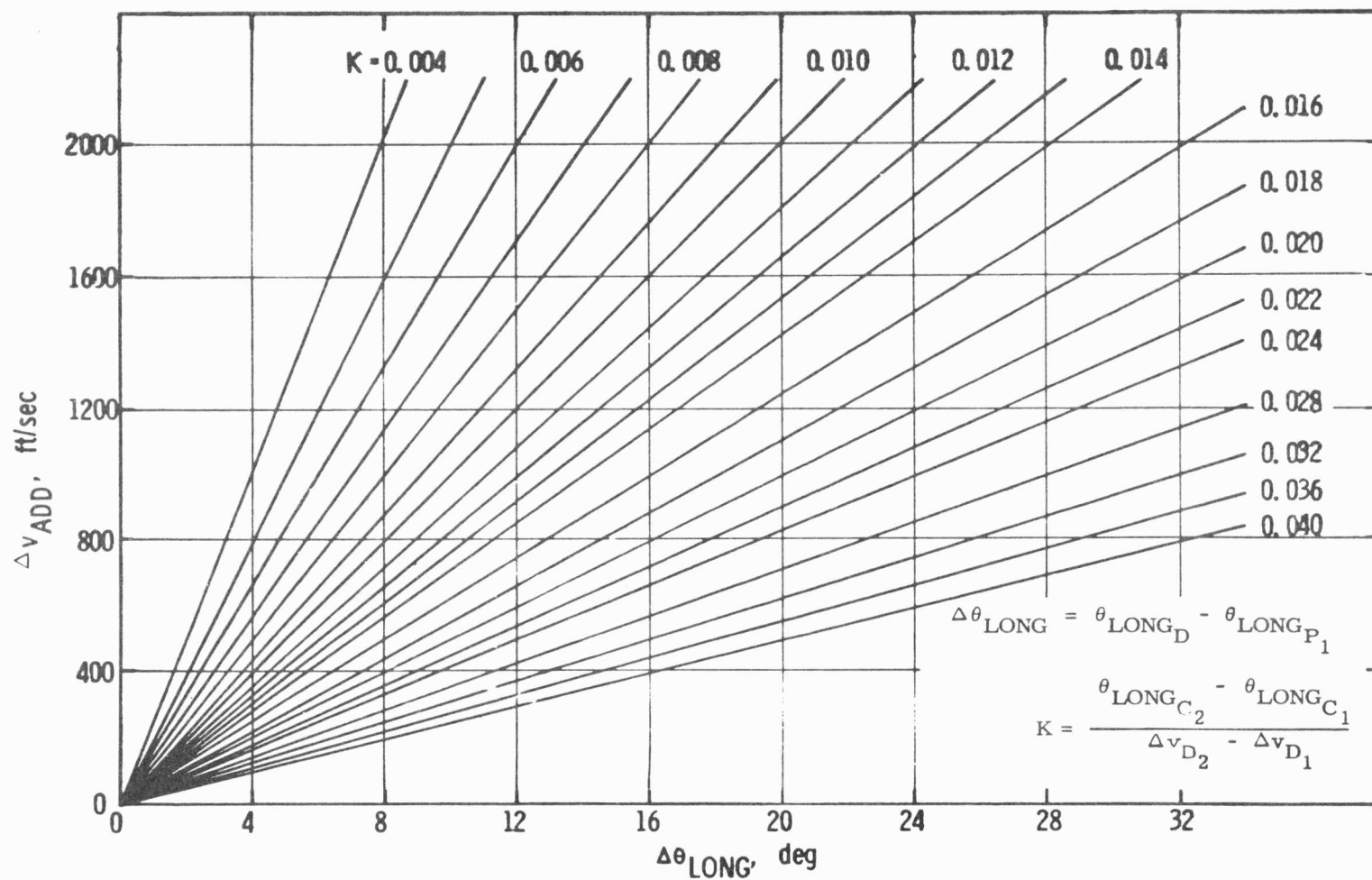


Figure 5.2.6-14a Increase in Δv_D to Produce a Desired Increase in θ_{LONG} : $K = 0.04$ to 0.004

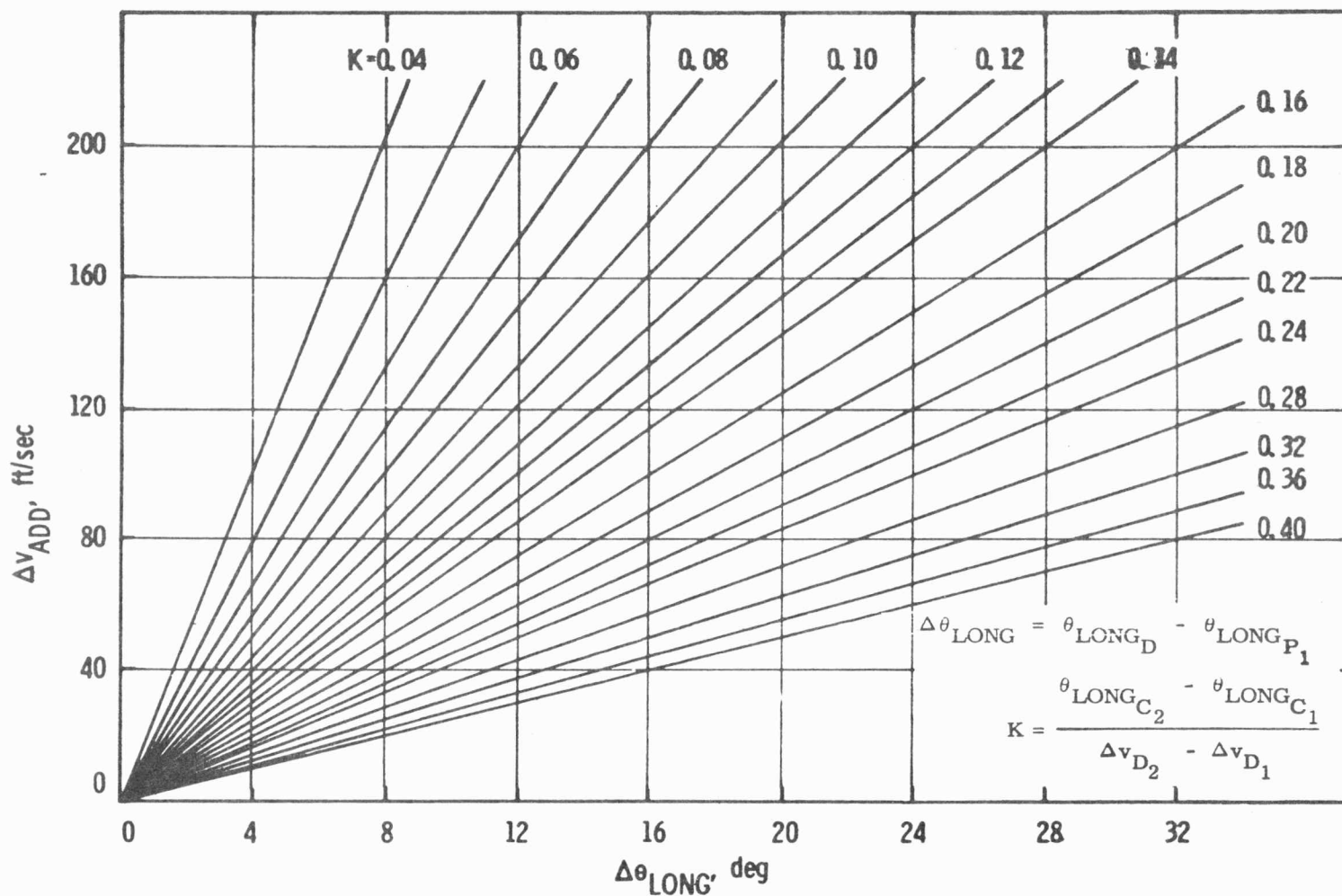


Figure 5.2.6-14b Increase in Δv_D to Produce a Desired Increase in θ_{LONG} : $K = 0.4$ to 0.04

2. Record $\theta_{\text{LONG}_{C_1}}$ and the last Δv_D^* input (Δv_{D_1}).
3. Proceed through to a precision solution.
4. Record the precision longitude ($\theta_{\text{LONG}_{P_1}}$).
5. Add ± 10 fps to Δv_{D_1} (to get Δv_{D_2}), and re-run the conic.
6. Record the Δv_{D_2} and the resulting $\Delta_{\text{LONG}_{C_2}}$.
7. Obtain value "K" by dividing by ± 10 (viz., $\Delta v_{D_2} - \Delta v_{D_1}$) the difference in $\theta_{\text{LONG}_{C_1}}$ and $\theta_{\text{LONG}_{C_2}}$.
8. Use "K" to get from Figure 5.2.6-14 the value ($\Delta v_{D_{\text{ADD}}}$) that must be added to Δv_{D_1} in order to obtain the required $\Delta_{\theta_{\text{LONG}}}$ (viz., $\theta_{\text{LONG}_D} - \theta_{\text{LONG}_{P_1}}$).
9. Use Δv_{D_3} (i.e., $\Delta v_{D_1} \pm \Delta v_{D_{\text{ADD}}}$) to re-run both conic and the precision solution. (Adding $\Delta v_{D_{\text{ADD}}}$ moves the landing site eastward; adding $-\Delta v_{D_{\text{ADD}}}$ moves the landing site westward.)

For an adjusted-landing-site return from transearth coast, the crew would initially enter a Δv_D input of zero—the same as for a minimum-fuel return. Recording the conic-solution longitude and the scalar Δv (VERB 06 NOUN 40), the crew would then allow the precision solution to complete. Should the precision-solution landing site be unacceptable, the crew would use the plus or minus of the Δv value observed in NOUN 40—rather than the zero Δv_D input—when adding ± 10 fps to obtain Δv_{D_2} . (See step 5 of reiteration procedure used for translunar coast.) For example, if the initial Δv_D input yielded an unacceptable landing site, and the value observed in NOUN 40 (R2) were 400 fps, the crew would add (step 5) +10 fps to +400 fps, yielding +410 fps for an eastward adjustment, or would add -10 fps to -400 fps, yielding -410 fps for a westward adjustment. Steps 6, 7, 8, and 9 are performed the same as for translunar coast.

* Near the upper limits of Δv or near the minimum-fuel Δv , adding or subtracting 10 fps to Δv_{D_1} can result in a Δv_{D_2} that is outside the program-constrained limits. To detect this, the crew should monitor VERB 06 NOUN 40 (register 2) immediately after the display of the vector Δv (output 6). NOUN 40 will display the scalar value of Δv , which will be exactly equal to Δv_{D_2} unless Δv_{D_2} is outside the limits. Should the latter occur, the scalar Δv observed in NOUN 40 will be the program-limited value. The program should be allowed to complete the precision solution in order to discover whether the desired landing site is achievable with the limited Δv ; if so, reiteration can be continued by adding a value less than ± 10 fps to Δv_{D_1} , i.e., a value that will not exceed the Δv limits.

5.2.6.5 Program Alarms

In addition to the anticipated outputs, the program will display an alarm under the following conditions:*

- a) Alarm code 00612 is displayed if the state vector at t_{IG} is within the lunar sphere of influence.
- b) Alarm code 00605 is displayed if the solution will not converge.
- c) Alarm code 00613 is displayed if the desired entry flight-path angle is unobtainable.
- d) Alarm code 20610 is displayed if the state vector at t_{IG} is below 400,000 ft.
- e) Alarm code 20607 is displayed whenever any of certain conic service routines used by P37 fail.
- f) Alarm code 20430 is displayed if the state vector extrapolated either to t_{IG} (during conic phase) or to t_2 (during the precision phase) is beneath the earth's surface.

P37 is not capable of targeting a return when the position of the spacecraft at time of ignition is within the lunar sphere of influence (LSI). Should an attempt be made to target such a return, alarm 00612 will alert the crew that the proper solution is not possible. The corrective action is to adjust the t_{IG} input such that the spacecraft will be outside the LSI at ignition. Note that the present spacecraft position is of no consequence: so long as the spacecraft state vector at t_{IG} lies outside of the LSI, the position when P37 is called can be either within the LSI, outside the LSI, or outside but on a trajectory that passes through. Again, since the essential concern is the position at t_{IG} , the corrective action for alarm 00612 is to select a later (or earlier) t_{IG} .

Although we have not been able to simulate a likely condition resulting in a nonconverging solution (alarm code 00605), we have, nevertheless, incorporated iteration counters as a safeguard against the possibility of getting into an infinite

* Alarms 00612, 00605, and 00613 are indicated by a PROG illumination, a flashing VERB 05 NOUN 09, and a display of the appropriate alarm code. Alarms 20610, 20607, and 20430 are POODOO alarms, indicated by a PROG illumination and a flashing VERB 37. For a POODOO alarm, the operator must key VERB 05 NOUN 09 ENTR for a display of the alarm code. To return to P37, he must depress KEY REL and RSET and then key 37 ENTR.

loop. Should an alarm 00605 occur during the conic computation, the recommended corrective action would be, first, to reiterate using a specified $\nu(t_2)_D$, i.e., other than zero; if the alarm still occurs, to reiterate using a different t_{IG} . Should an alarm 00605 occur during the precision computation, the recommended corrective action would be to reiterate with an increased Δv_D ; the resulting decrease in transit time should require fewer iterations to converge on a solution. Again, the second thing to try would be to change the t_{IG} .

Although it would require lengthy explanation, we have become convinced since the original design of P37 that a condition triggering alarm code 00613 will never occur. Nevertheless, should by some remote and unforeseen circumstance the desired entry flight path not be obtainable, a possible corrective action would be either to increase the Δv_D or to adjust the $\nu(t_2)_D$.

P37 cannot be used for targeting trajectories begun below 400,000 ft above the Fischer ellipsoid. Accordingly, the DSKY will flash VERB 37, for an alarm code 20610, should a t_{IG} be inadvertently entered that would occur below the earth-entry interface. The recommended corrective action would be to decrease t_{IG} such that it occur above 400,000 ft.

The recommended action for alarm 20607 is to check for valid inputs.

For an alarm 20430 during the conic phase, the crew would select an earlier t_{IG} ; an alarm 20430 during the precision phase is rare and would be corrected by increasing Δv_D or adjusting t_{IG} in order to reduce trajectory perturbations caused by the lunar gravitational field.

5.2.6.6 Additional Restrictions

In addition to its being restricted from transfer trajectories begun within the lunar sphere of influence, the limitations of P37 are (1) it does not target trajectories begun from certain positions in the vicinity of the moon (Figure 5.2.6-15), though not within its sphere of influence, and (2) it does not target out-of-plane maneuvers. Regarding trajectories targeted from the vicinity of the moon, the number of variables precludes our defining an exact envelope of no solution. Therefore, for a return from any area approximating that shown in Figure 5.2.6-15, we recommend that VERB 16 NOUN 38 be used to monitor the program as it attempts to converge to a precision solution. Monitoring the state-vector time (as described in paragraph 5.2.6.3.2) is necessary in this instance because, though t_{IG} fall outside the LSI, the post-ignition trajectory would, if the solution converged, pass within the sphere of

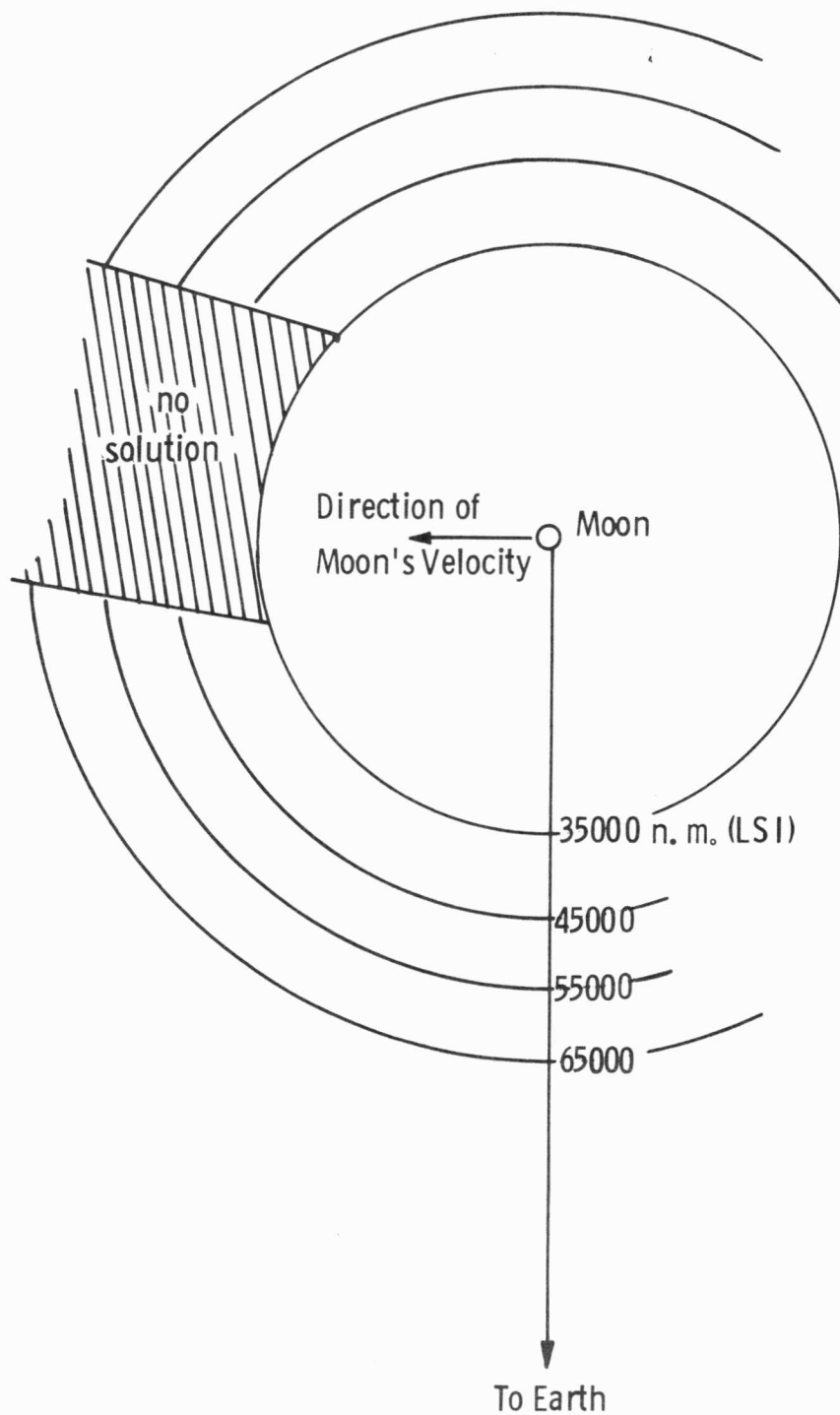


Figure 5.2.6-15 Area, Near Lunar Sphere of Influence, Where P37 Will Not Converge to a Precision Solution

influence. The solution does not converge, however, nor is there an alarm; the only indication is (monitoring NOUN 38) the abnormal behavior of state-vector time. The corrective action would be to terminate integration (VERB 96 ENTR) and to reenter the program with an earlier t_{IG} , an increased Δv_D , or both.

The reason that P37 is designed to provide only in-plane solutions is to minimize fuel expenditure and program complexity. The one exception to the in-plane-only solutions is when the spacecraft is in the vicinity of the moon (though outside its sphere of influence) and there is a near collinearity of the r -vector and v -vector, viz., within $1-1/2$ deg. In this situation, when the actual plane cannot be determined, an arbitrary plane is defined having the minimum possible inclination, i.e., such that the inclination of the post-maneuver orbit is equal to the angle formed by the pre-maneuver position vector and the earth's equatorial plane. Again, this occurs only when \underline{r} and \underline{v} are nearly collinear.

Also in the category of program limitations are the constraints regarding landing-site adjustment. The in-plane-only limitation is, itself, one constraint on landing site; consequently, the crew has very little control over the landing latitude. The second constraint is related to the discontinuity that exists regarding velocity change and transit time. For some outbound pre-abort trajectories (see Figures 5.2.6-8d and -16), the solution of the return-trajectory problem is multivalued for a given Δv_D ; consequently, a small change in Δv_D may result in a change from a direct-return to a return-through-apogee solution. (See Figure 5.2.6-2.) In iterating for landing-site selection, the crew may observe, for a small change in Δv_D , a very large change in t_{21} and, of course, in landing site. As evidenced by Figure 5.2.6-16, the area in which the discontinuity can occur is quite small; encountering it, the crew has the option of iterating either for a suitable landing site within the realm of direct-return solutions or for one within the realm of return-through-apogee solutions. To more precisely locate the discontinuity, the crew can reiterate for a solution using one-half the difference in the two preceding Δv_D s. The procedure can be repeated, with progressively smaller differences in Δv_D , until the desired result is obtained.

5.2.6.7 Program Coordination

Although the execution of P37 requires only an operational command-module computer (CMC) and does not require the inertial subsystem (ISS) to be on, timing considerations will usually best be served if the ISS is operating and the IMU is aligned before P37 is entered. Considering (1) that the ISS is required to be on for at least 15 minutes before the execution of the thrusting program (P40 or P41), (2) that normally

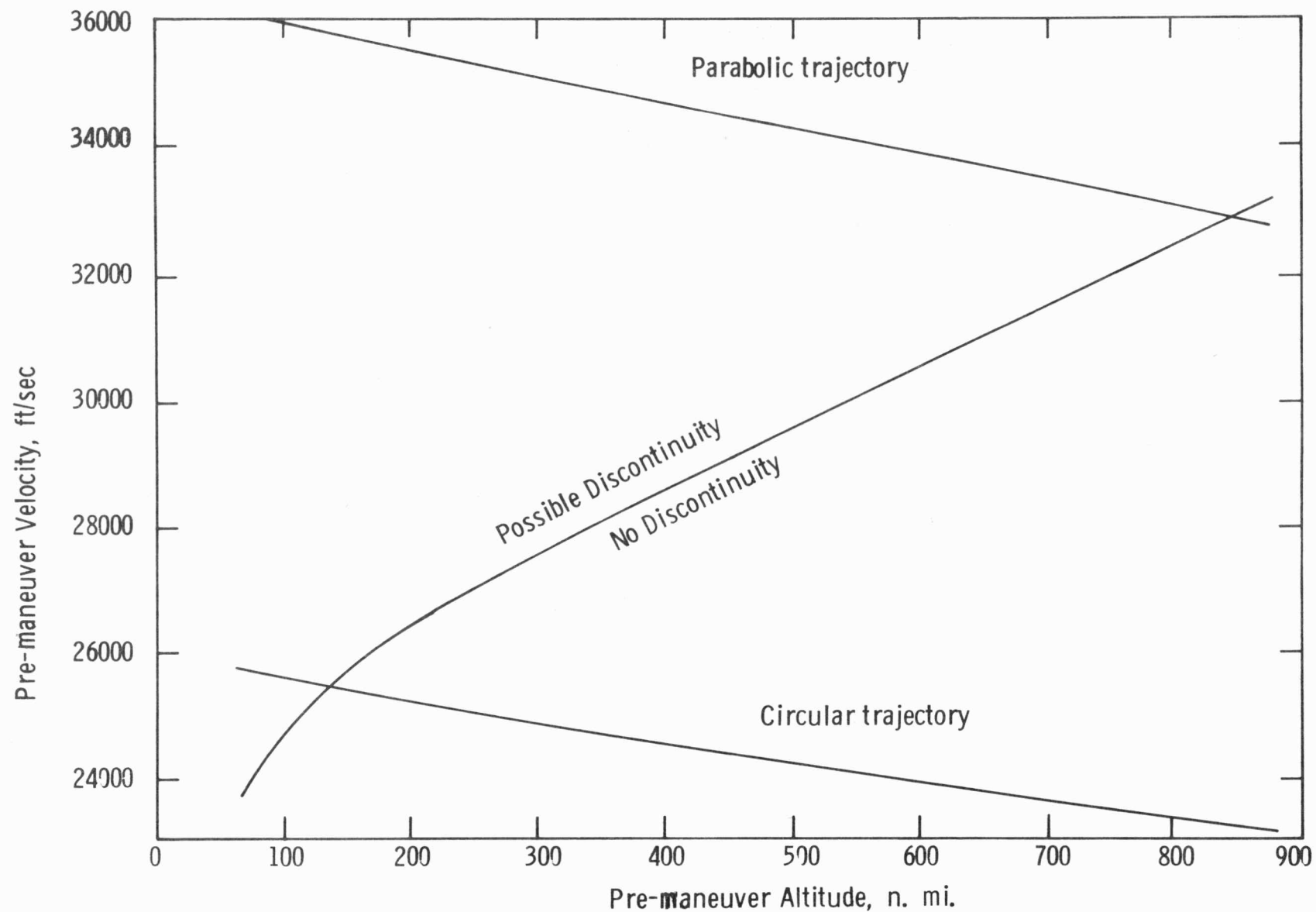


Figure 5.2.6-16 Pre-maneuver Conditions Where a Possible Discontinuity Exists in the Relationship Between Δv and Transfer Time

the prethrust program (P37) requires, at most, 35 to 40 minutes to complete, and (3) that the DAP Data Load Routine (R03) must be performed before the P37 precision solution can be computed, we recommend the following as the normal sequence when timing is critical and an actual burn is anticipated:

- a) Perform Autopilot Data Load (R03)
- b) Perform Orientation Determination Program (P51)
- c) Perform Return-to-earth Targeting (P37)
- d) Begin SPS or RCS Thrusting Program (P40 or P41)
- e) If the MGA displayed by P37 was greater than 45 deg, exit P40 (or P41) and perform P52 Option A, "Preferred Orientation," as soon as the thrusting program enters the Attitude Maneuver Routine (R60) and displays the desired gimbal angles. (The crew should expect here to observe essentially the same MGA as displayed by P37.) Upon completion of P52, reenter and complete P40 (or P41). If the MGA displayed by P37 (and now R60) was less than 45 deg, but greater than zero, the crew has the option of either accepting the existing alignment, thereby conserving RCS fuel, or entering P52 to perform a "preferred orientation." Accepting the existing alignment, the crew allows the thrusting program to continue; rejecting alignment, the crew proceeds as though the MGA had been greater than 45 deg, i.e., completes Option A of P52 and then reenters the thrusting program at the beginning.

The exception, when the above sequence might not be appropriate, or desired, is when a thrusting maneuver is not intended to immediately follow P37. For example, should the crew wish merely to exercise P37, without intending to use the targeting information for an actual burn, or should the crew intend a burn, but with a several-hour delay before ignition, then P37, requiring only an operational CMC, can be performed before the IMU alignment is determined. [Since IMU realignment (P52) will be necessary should more than 3 hours elapse between IMU alignment determination (P51) and t_{IG} , there is little or no advantage in this case in performing P51 before P37.] An alternate sequence, therefore, might be as follows:

- a) Perform P37 through propulsion-system option selection.
- b) Perform DAP Data Load Routine (R03) unless no burn is anticipated or R03 has been performed earlier.
- c) Continue P37 to completion.
- d) Within 3 hours of t_{IG} , perform IMU Orientation Determination Program (P51).

- e) Enter SPS or RCS thrusting program (P40 or P41); when the thrusting program enters the Attitude Maneuver Routine (R60) and the DSKY flashes VERB 50 NOUN 18, "Please perform auto maneuver," observe whether the "final desired gimbal angle" is acceptable to the crew and, in any case, less than 45 deg. If the final MGA is not acceptable, exit the thrusting program and perform IMU Realign Program (P52), Option A, "Preferred Orientation." If the final MGA is acceptable to the crew and is less than 45 deg, proceed with R60 and allow the thrusting program to continue to completion.
- f) Upon completion of P52 Option A (unacceptable final MGA), reenter and perform SPS or RCS thrusting program (P40 or P41).

Additional factors regarding IMU alignment are related to RCS fuel economy. When a fuel-critical return using RCS thrusting is anticipated, it becomes especially important that as little RCS fuel as possible be used in aligning the IMU. Accordingly, when RCS fuel supply is critical, the crew should avoid, if possible, the necessity of entering P52. One means of avoiding the need for realigning the IMU is to visually orient the spacecraft during P51, such that the spacecraft y-axis will lie approximately normal to the \underline{y} , \underline{r} plane, and then to coarse align the IMU to 0,0,0 gimbal angles. P51 can then be completed and the IMU left stabilized at an orientation that should ensure a "final desired middle gimbal angle" of less than 45 deg for any trajectory targeted by P37, which computes only in-plane solutions, i.e., local-vertical thrust-vector component $y = 0$. Again, however, to avoid performing IMU Realignment (P52), P51 must be completed within 1 to 3 hours of t_{IG} .

5.2.6.8 Returns Using Lunar-module Descent Propulsion System (LM DPS)

Should, for some reason, the crew wish to use the LM DPS for the return-to-earth maneuver, the t_{IG} and Δv precision outputs of P37 can be used as the manually entered inputs for targeting an External- Δv burn with P30. There is, however, one important exception: in the vicinity of the moon, when \underline{r} and \underline{y} may be within 1-1/2 deg collinearity it may be necessary for P37 to compute an arbitrary return transfer plane (paragraph 5.2.6.6); the Δv output, in that case, would not be valid for use with P30. (Use P21 to determine flight-path angle (γ) at desired t_{IG} ; if γ is within 1-1/2 deg of +90 or -90 deg, the P37 Δv cannot be used with P30.)

5.2.6.9 Restart

P37 is not restart protected. Should a restart occur, the program must be reselected and all inputs re-entered.

6.2.1 P40, Service Propulsion System (SPS) Maneuver Program—CMC

The powered flight guidance program, P40, handles the timing of SPS maneuvers. During burns, P40 maintains the CSM state vector, guides the thrust direction so as to achieve the desired velocity at the end of the maneuver, and provides the crew with a monitor of the maneuver's progress. P40—which may be used when a change-of-orbit maneuver is required—and the SPS are used for big burns with a manually controlled RCS trim maneuver at the end.

For a GNCS-controlled maneuver, P40 is used for a large velocity-to-be-gained; i.e., when \underline{v}_G is greater than, or equal to,

$$\frac{F_{\text{SPS}}}{m} \cdot \Delta t_{\text{MIN}}$$

In the expression above, F_{SPS} is the thrust of the SPS engine (about 20,500 lb), m is the mass of the total vehicle (including the LM if it is attached), and Δt_{MIN} is the minimum burn time for which the particular SPS engine being considered has been successfully tested. Currently, Δt_{MIN} equals 0.5 sec.

A prethrust program, P3x, establishes the parameters needed for thrust control guidance. After the appropriate P3x has been performed, the astronaut must not select another P3x, P7x, P17, or P23 before the burn. These programs use some of the same variable computer storage locations and would destroy the thrusting parameters established by the original P3x for this burn. Since mark incorporation would change the current state vector without correspondingly changing the thrusting parameters, P20 should not be selected between P3x and P40. If P20 had been previously selected, however, it may continue to run in the background. (The mark incorporation function is turned off by P3x.)

P40 uses the AVERAGEG routine for state vector updating, and cross-product steering for inputs to the TVC DAP, which controls the spacecraft attitude by positioning the engine bell during the burn.

6.2.1.1 State Vector Updating (AVERAGEG)

To keep the state vector up to date, the AVERAGEG routine takes into account two kinds of acceleration effects:

- a. Gravity—by averaging the gravitational acceleration vector over 2-sec increments of time
- b. Thrusting—by discrete velocity increments as measured by the PIPAs.

The state vector is updated by AVERAGEG every 2 seconds. AVERAGEG is used during burns because of its speed in updating. It should be terminated as soon as possible after the burn, however, to avoid accumulation of PIPA bias errors. Refer to subsection 6.1 for a more detailed discussion of AVERAGEG.

6.2.1.2 Cross-Product Steering (External $\Delta \underline{v}$ and Lambert Aimpoint)

Cross-product steering is used to guide the thrust direction. The two modes, External $\Delta \underline{v}$ and Lambert aimpoint, use the cross-product steering concept to control the thrust direction along the velocity-to-be-gained (\underline{v}_G) vector and to terminate thrust when the desired velocity increment has been achieved. The two modes differ in method of computing \underline{v}_G . External $\Delta \underline{v}$ is characterized by a non-rotating burn and therefore uses a single value of v_R (required velocity) in its computations. Lambert aimpoint periodically recomputes v_R to achieve an intercept with the specified target vector at the specified time.

In External $\Delta \underline{v}$, since the change of velocity cannot be made instantaneously, the routine uses a compensated inplane velocity to compute \underline{v}_G rather than the actual desired-velocity-change vector.

The 2-second cycles of the cross-product steering functions often do not allow enough time to complete a Lambert computation in each cycle. Consequently, values from the last complete Lambert computation are used to determine \underline{v}_G by extrapolating current values until new data are available from a complete Lambert computation. For a detailed explanation of External $\Delta \underline{v}$ and Lambert aimpoint, refer to subsection 6.1.

6.2.1.3 P40 Procedures

Tables 6.2.1-I and -II show P40 displays and extended verbs, respectively. Figure 6.2.1-1 is the program flowchart. Before entering P40, the Autopilot Data Load Routine (R03) and a prethrust program (P3x) must be performed. In addition, the IMU must be powered up and aligned.

The crew selects P40 (via the DSKY) at a time, specified by crew procedures, to allow sufficient time before ignition for prethrust activities, such as arming the

TABLE 6.2.1-1
DISPLAYS ASSOCIATED WITH P40 (SHEET 1 OF 2)

DSKY	Initiated By	Purpose	Condition	Register
V05 N09E	Astronaut	Verify PROG alarm	.00205 bad PIPA reading detected 00210 ISS not on 00220 IMU orientation unknown 01301 arc-sine or arc-cosine argument too large 01407 velocity-to-be-gained increasing 01703 time of ignition slipped	R1 xxxxx* R2 xxxxx R3 xxxxx
FL V50 N18	R60	Display required gimbal angles	OGA-roll IGA - pitch MGA - yaw	R1 xxx.xx deg R2 xxx.xx deg R3 xxx.xx deg
V06 N18	R60	Display of final gimbal angle	OGA IGA MGA	R1 xxx.xx deg R2 xxx.xx deg R3 xxx.xx deg
FL V50 N25	P40	Please perform SPS gimbal test drive option	00204 gimbal drive test option	R1 00204
V06 N40	P40	Display	Time from t_{IG} Velocity to-be-gained Sum of acquired velocity	R1 xxBxx min, sec R2 xxxx. x ft/sec R3 xxxx. x ft/sec
FL V99 N40	P40	Request SPS engine-on enable	---	---
FL V97 N40	R40	Low thrust detected	---	---
FL V16 N40	P40	Burn complete	Time from cutoff Remaining \underline{v}_G Sum of velocity acquired	R1 xxBxx min, sec R2 xxxx. x ft/sec R3 xxxx. x ft/sec
FL V16 N85	P40	Display remaining \underline{v}_G	Components of \underline{v}_G	R1 xxxx. x ft/sec R2 xxxx. x ft/sec R3 xxxx. x ft/sec

*The alarm codes are displayed as follows:
R1 contains the first alarm following error reset.
R2 contains the second alarm following error reset.
R3 contains the most recent alarm.

TABLE 6.2.1-I
DISPLAYS ASSOCIATED WITH P40 (SHEET 2 OF 2)

DSKY	Initiated by	Purpose	Condition	Register
FL V16 N44	Astronaut	Display orbital parameters (R30)	Apogee altitude Perigee altitude Time of free fall	R1 xxxx. x n. mi. R2 xxxx. x n. mi. R3 xxBxx min, sec
FL V16 N54	R31	Display	Range Range rate Theta	R1 xxx. xx n. mi. R2 xxxx. x ft/sec R3 xxx. xx deg
V16 N62	Astronaut	Display	Velocity Rate of altitude change Altitude	R1 xxxxx. ft/sec R2 xxxxx. ft/sec R3 xxxx. x n. mi.

TABLE 6.2.1-II
EXTENDED VERBS FOR USE WITH P40

VERB	Identification	Purpose	Remarks
82 ENTR	Do R30	Compute and display relevant orbital parameters	DSKY displays apogee, perigee; and time of free fall
83 ENTR	Do R31	Display rendezvous parameters	DSKY displays range, range rate and theta, the angle between local horizontal and the spacecraft X-axis

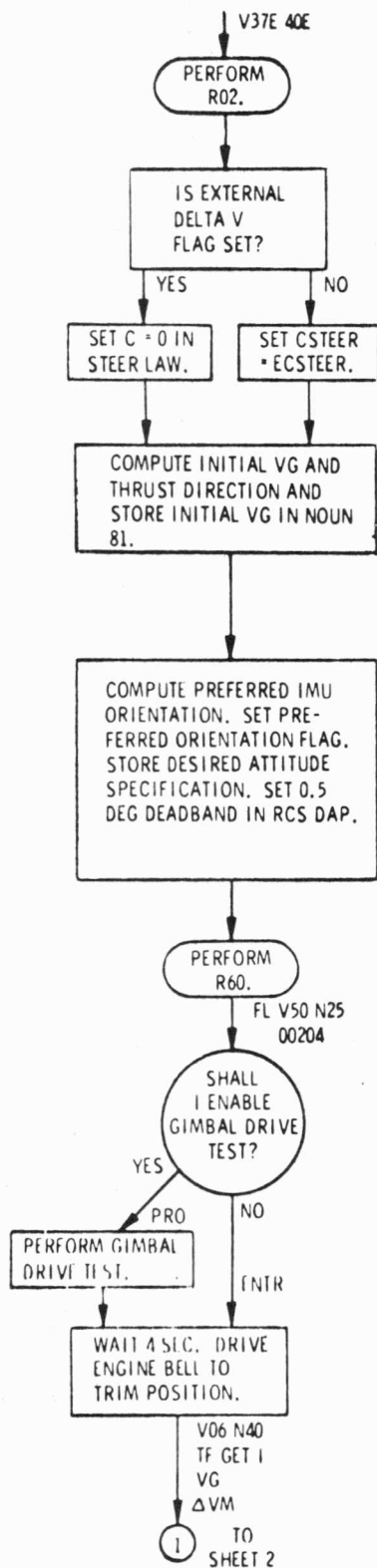


Figure 6. 2. 1-1. SPS Maneuver Program (P40) (Sheet 1 of 3)

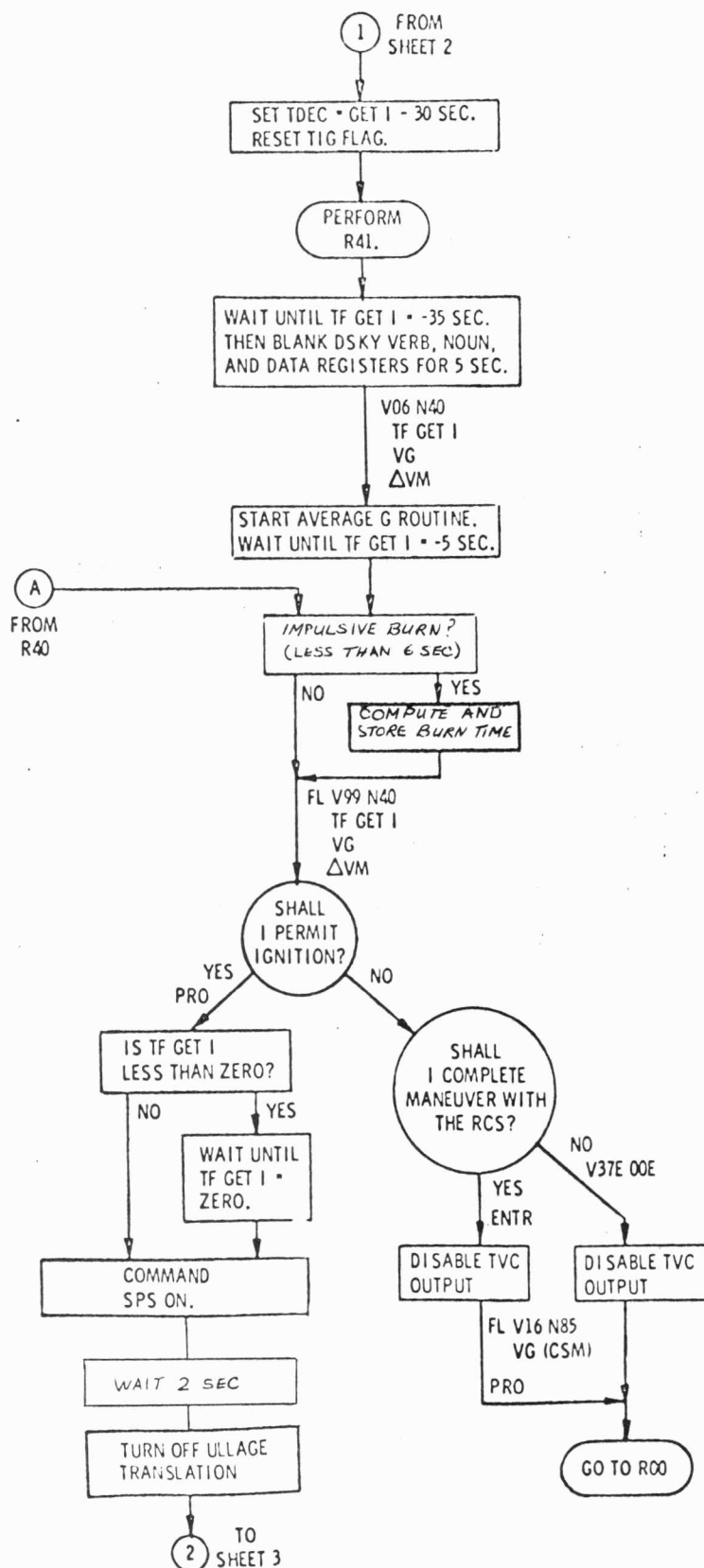
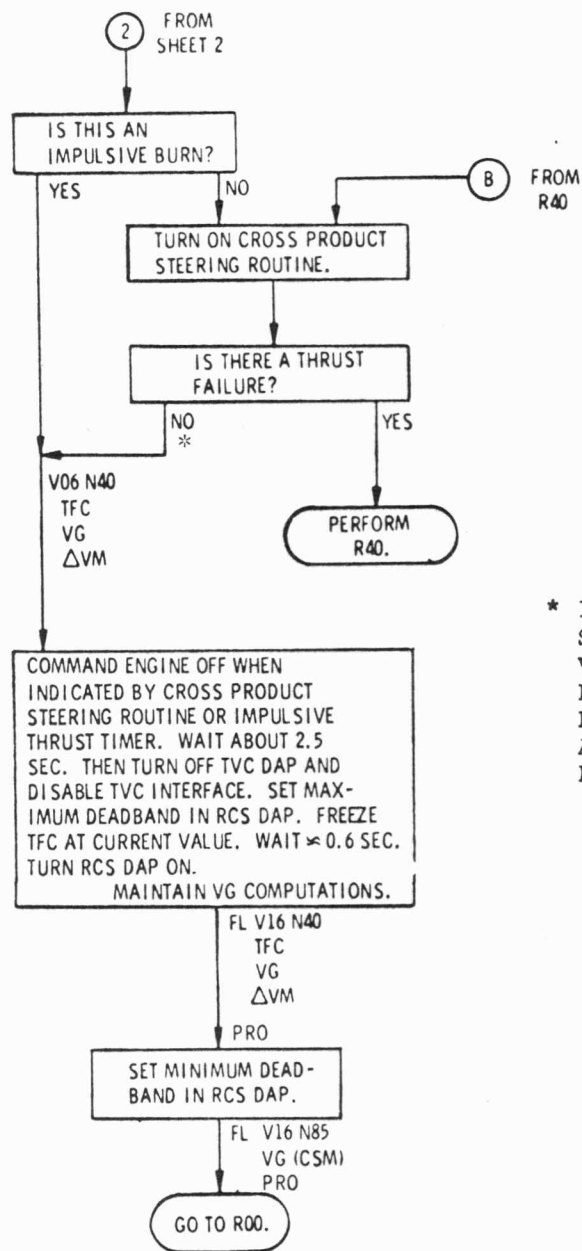


Figure 6.2.1-1. SPS Maneuver Program (P40) (Sheet 2 of 3)



* IF CROSS PRODUCT STEERING DETECTS VG INCREASING PROG LT--ON. FOR DISPLAY OF ALARM CODE 1407 KEY V5N9E.

Figure 6. 2. 1-1. SPS Maneuver Program (P40) (Sheet 3 of 3)

SPS and TVC, and performing R60. The program performs the IMU Status Check Routine (R02) and illuminates the PROG light if the ISS is off (alarm code equals 00210) or the IMU orientation is unknown (alarm code equals 00220).

At the completion of R02, the program computes the initial \underline{v}_G and thrust direction and the preferred orientation matrix and then enters the Attitude Maneuver Routine (R60) and flashes VERB 50 NOUN 18. The desired gimbal angles are displayed to 0.01 deg in the following registers:

R1 = OGA, roll
R2 = IGA, pitch
R3 = MGA, yaw.

If the PROG light goes on at this point and the alarm code is 01301, the desired gimbal angles are indeterminate because the initial \underline{v}_G is collinear with the stable member Y-axis. A maneuver to the desired attitude would produce gimbal lock.

If the crew chooses to have the attitude maneuver performed by the autopilot, the SC CONT switch must be placed in CMC, the CMC mode switch in AUTO, and then PRO keyed in response to VERB 50 NOUN 18, signaling the RCS DAP to begin the maneuver via R60.

During the maneuver, a non-flashing VERB 06 NOUN 18 displays the final gimbal angles, and the crew monitors the maneuver on the FDAI ball and needles. If gimbal lock is approached, or if it is desired to perform the entire maneuver manually, the crew uses the RHC to complete the maneuver. (Once the RHC is removed from detent, the automatic maneuvering routine ceases and can be re-initiated by responding with a PRO to the flashing VERB 50 NOUN 18.) A VERB 50 NOUN 18 display comes up upon completion of the R60 maneuver. The crew can then switch to SCS control and verify manual TVC. To exit from R60, the crew keys ENTR on VERB 50 NOUN 18.

Upon completion (or termination) of R60, the DSKY displays a flashing VERB 50 NOUN 25 with R1 containing 00204 (i.e., please perform SPS gimbal drive test option). The crew now arms the SPS and TVC. If the time to ignition is too short to allow the test to be performed, the crew can key ENTR. Normally, the crew keys PRO and monitors the test on the gimbal position indicator (GPI). In 2-second intervals, the SPS pitch gimbal is driven from 0 deg to +2 deg, from +2 deg to -2 deg, and from -2 deg to 0 deg. The SPS yaw gimbal then undergoes the same process.

After a 4-second delay, the program drives the engine bell to the trim position. Then the DSKY displays (and repeats every second) VERB 06 NOUN 40; the registers contain the following:

- R1 = time from t_{IG}
- R2 = magnitude of velocity-to-be-gained
- R3 = sum of velocity increments acquired so far.

R1 is negative until t_{IG} . R2 initially contains the total velocity-to-be-gained and decreases as the maneuver proceeds. R3 should remain close to zero until ullage begins.

The program at this time enters the State Vector Integration Routine (R41), which integrates the CSM state vector ahead to $t_{IG}-30$ seconds. If R41 is not completed before $t_{IG}-42.5$ seconds, a program alarm (code 01703) is generated and the time of ignition is slipped until the integration is completed.

At $t_{IG}-35$ seconds, the DSKY is blanked for 5 seconds, then the VERB 06 NOUN 40 display returns. This is the beginning of the AVERAGEG and v_G updating cycles. From $t_{IG}-30$ until $t_{IG}-25$ seconds, the crew should watch R3 of the DSKY to be sure it does not exceed 2.0 ft/sec—a condition that indicates excessive PIPA bias and possible termination of the burn.

The crew should begin ullage shortly before t_{IG} —at a time determined from tables, depending on SPS fuel loading and the vehicle configurations. At this time, R3 will start to increase.

At $t_{IG}-5$ seconds, the DSKY display changes to flashing VERB 99 NOUN 40, requesting the SPS engine ignition go-ahead signal. The program provides the crew with the following three choices:

- a. Avoiding the burn altogether by keying VERB 34 ENTR or by selecting a new program (VERB 37 ENTR xx ENTR)
- b. Completing the maneuver under RCS power by keying ENTR
- c. Going ahead with the SPS burn by keying PRO.

The program commands SPS ignition at t_{IG} and displays a non-flashing VERB 06 NOUN 40. The SPS THRUST light goes on, and the crew will feel an acceleration

of approximately 0.2 to 1.0 g. If the crew fails to key PRO before t_{IG} , it may still PRO and the engine will light instantly.

During the burn, the astronaut should avoid using extended verbs since a VERB 97 display (low thrust) could be masked (i.e., not displayed on DSKY). In the Lambert mode, the computer may not have enough VAC area to perform both the Lambert computations and the extended verb. R1 displays time from engine cutoff. If R2 is increasing or if the PROG light goes on and alarm code 01407 occurs, there was probably an error in the initial attitude maneuver.

The crew can monitor the pitch and yaw attitude errors, as determined by the TVC autopilot, on the FDAI needles.

During the burn, if the system should detect a bad PIPA reading, the program will store an alarm code of 00205. The astronaut should switch to SCS control. If low thrust is detected by the computer, the program enters the Thrust Fail Routine (R40). The DSKY displays flashing VERB 97 NOUN 40 requesting action on thrust failure. (R40 is discussed in detail in paragraph 6.2.1.5.1.)

At cutoff time (t_{CO}), the program shuts off the SPS engine and the SPS THRUST light goes out. The DSKY displays a flashing VERB 16 NOUN 40 to indicate completion of the SPS burn; the crew replies by keying PRO. After 2 seconds, the DSKY displays a flashing VERB 16 NOUN 85 (the three components of the remaining \underline{v}_G , in control coordinates). The crew should use the RHC and THC to null the remaining \underline{v}_G to a value specified in the checklist. The crew keys PRO to get to the flashing VERB 37.

The crew may desire to review the post-burn orbital parameters (R30), or it may desire to review the range and range rate to the LM (R31/R34).

AVERAGEG will continue running until a new major mode is selected; therefore this selection must be made immediately to avoid accumulation of PIPA bias errors.

6.2.1.4 Time Lines

Figure 6.2.1-2 relates the P40 flowchart to crew observance and response.

COMPUTER PERFORMANCE

ASTRONAUT/DSKY

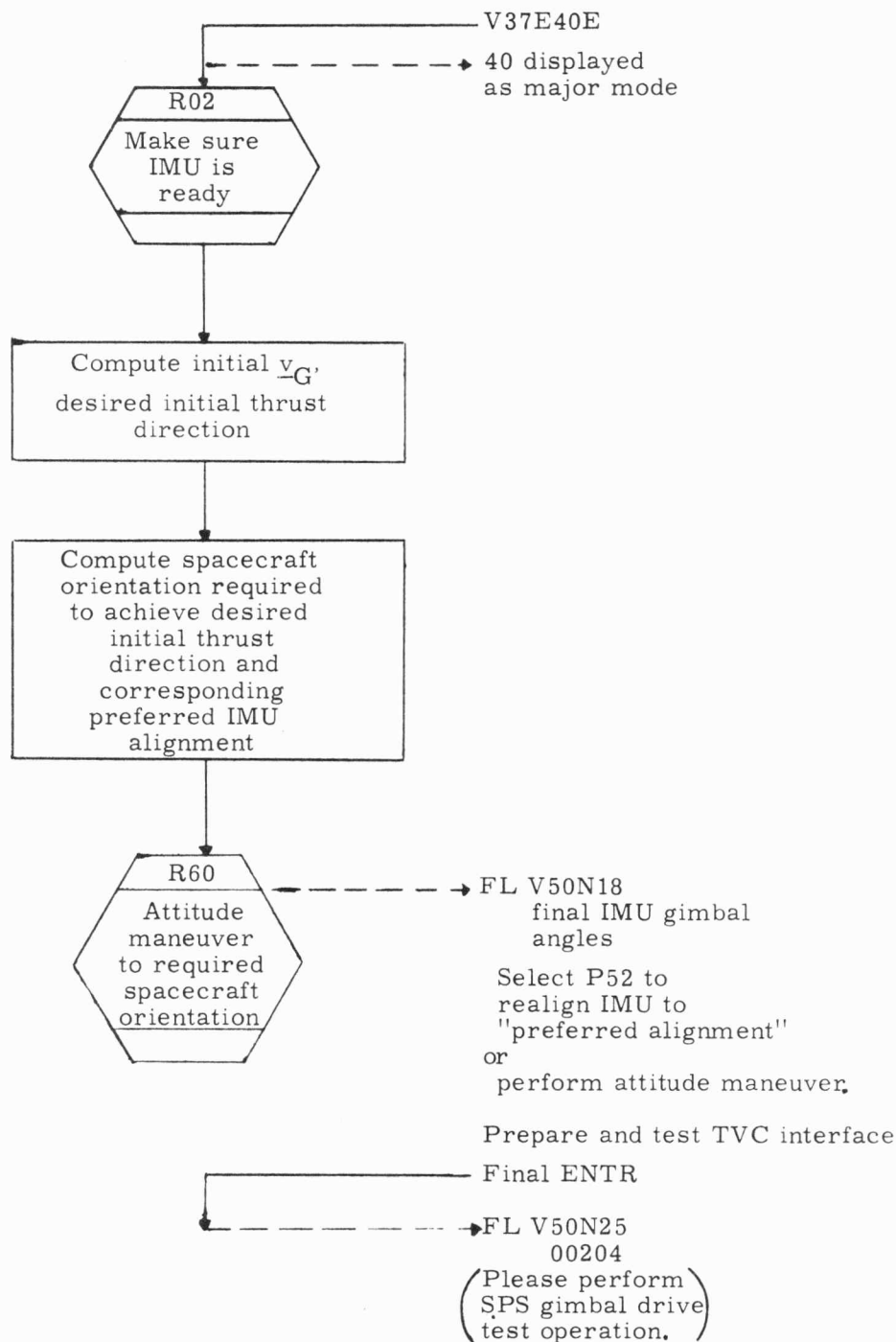


Figure 6. 2. 1-2. Time Lines of SPS Maneuver Program (P40)
(Sheet 1 of 4)

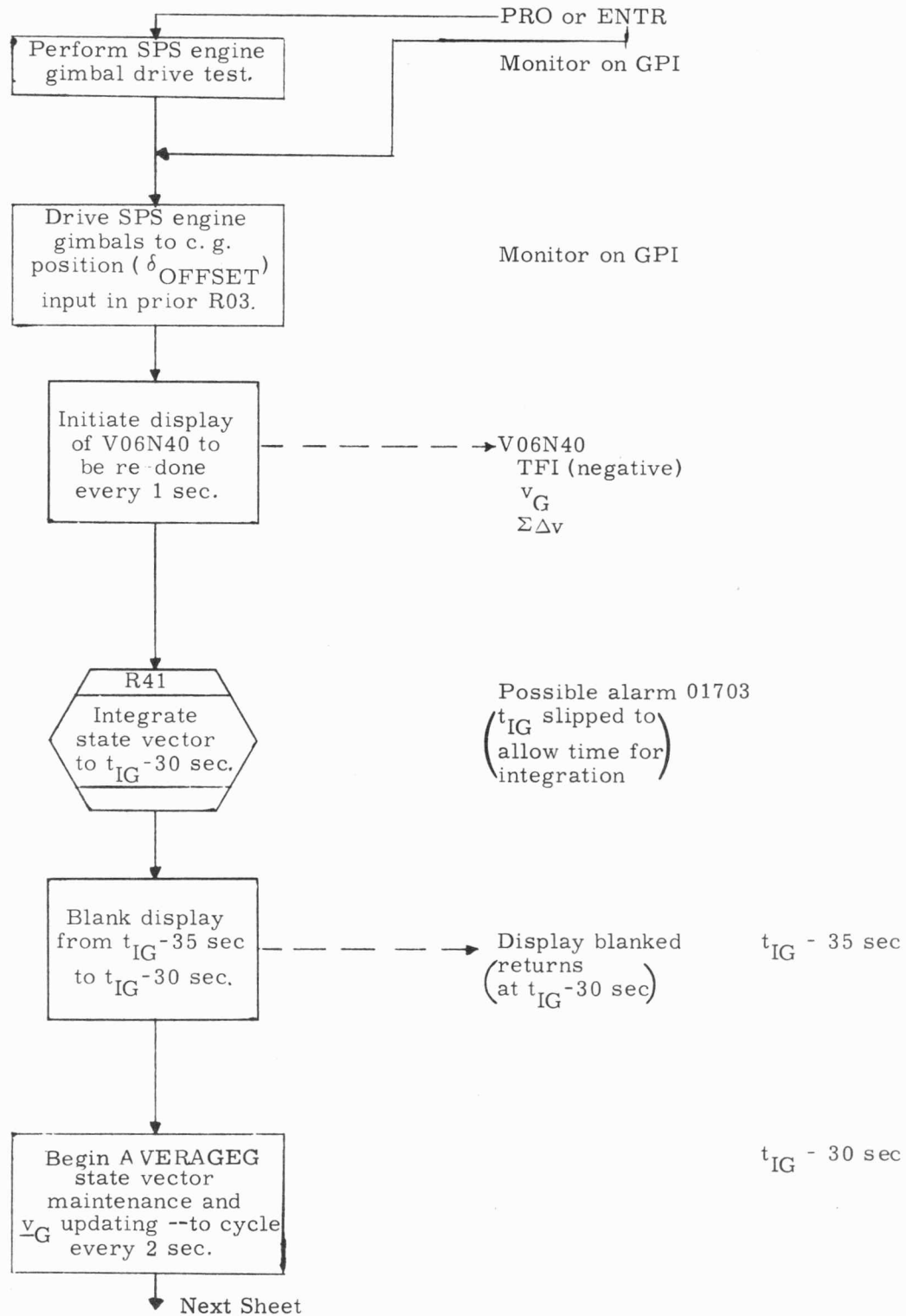


Figure 6.2.1-2. Time Lines of SPS Maneuver Program (P40)
(Sheet 2 of 4)

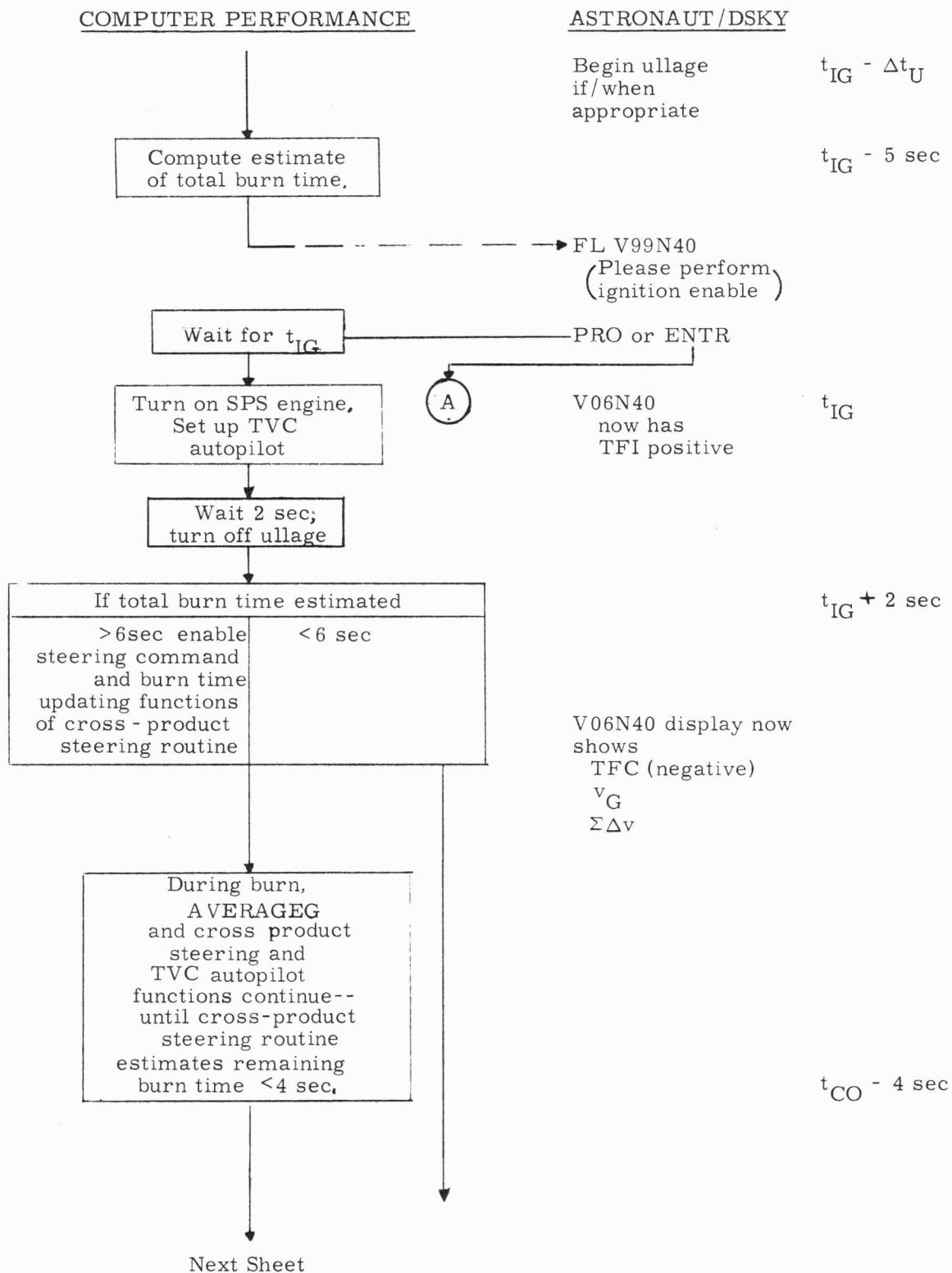


Figure 6.2.1-2. Time Lines of SPS Maneuver Program (P40)
(Sheet 3 of 4)

COMPUTER PERFORMANCE

ASTRONAUT/DSKY

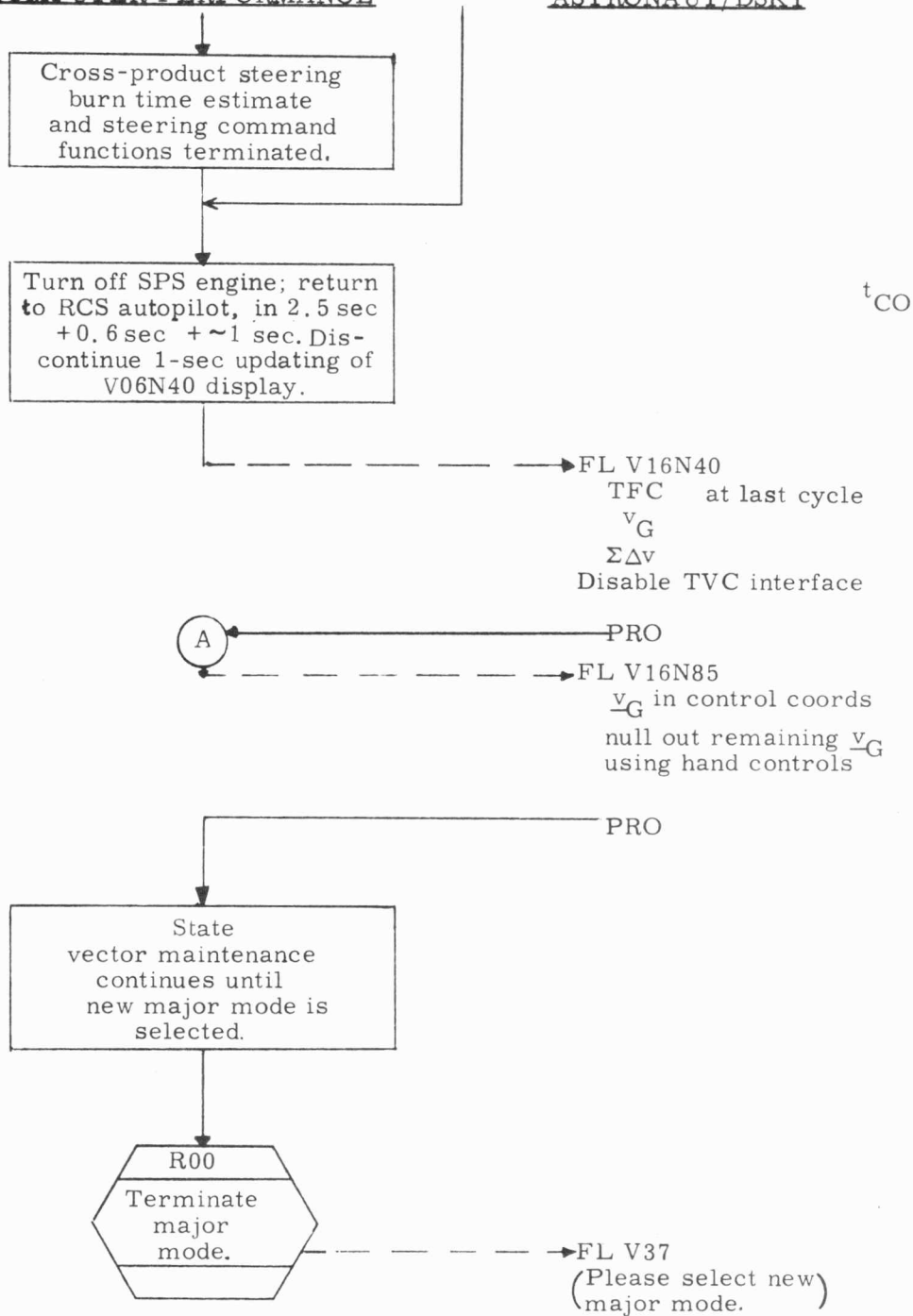


Figure 6.2.1-2. Time Lines of SPS Manuever Program (P40)
(Sheet 4 of 4)

6.2.1.5 Routines Associated with P40

6.2.1.5.1 SPS Thrust Fail Routine.—The SPS Thrust Fail Routine (R40) is automatically selected by P40 when low thrust is detected. Figure 6.2.1-3 gives a brief logical flow of R40. A flashing VERB 97 NOUN 40 notifies the crew of the thrust fail. If the engine comes back on at full strength, the crew can key PRO to continue the burn. To perform a manual thrust, the crew turns the DIRECT THRUST switch to ON and keys PRO.

To terminate the burn and attempt re-ignition or to attempt the maneuver by RCS power, the crew should key ENTR. Control will be returned to P40, where the time from t_{IG} display (R1) will be set to 59 min 59 sec, and the VERB 99 flash (occurring in about 2.8 seconds from return of control to P40) will behave as in a late ignition. The crew should key PRO for immediate ignition. The crew may choose to switch control of the burn immediately to the SCS. To terminate the burn altogether, the crew keys VERB 34 ENTR and turns the ΔV THRUST-A and -B switches to OFF when a new major mode has been requested.

6.2.1.5.2 State Vector Integration Routine.—Figure 6.2.1-4 is a flowchart of the State Vector Integration Routine (R41). R41 is automatically selected by P40, P41, P47, P61, and P62. The purpose of this routine is to integrate the state vector ahead to the time that the AVERAGEG routine will be turned on by the thrusting program. If the state vector integration cannot be completed before the specified time, a program alarm occurs (alarm code equals 01703) and the t_{IG} is slipped.

6.2.1.6 Alarms

A list of alarm codes which may occur in P40 follows; detailed description of procedures to follow upon occurrence of these alarms is given below.

- a. Alarm code 00205 occurs if a bad PIPA reading is detected.
- b. Alarm code 00210 occurs if the ISS is not on.
- c. Alarm code 00220 occurs if the IMU orientation is not known.
- d. Alarm code 01301 occurs if the arc-sine or arc-cosine argument is too large.
- e. Alarm code 01407 occurs if the velocity-to-be-gained is increasing.
- f. Alarm code 01703 occurs if the t_{IG} is slipped.

Alarm code 00205 may occur during the thrusting maneuver. The crew should switch to SCS control.

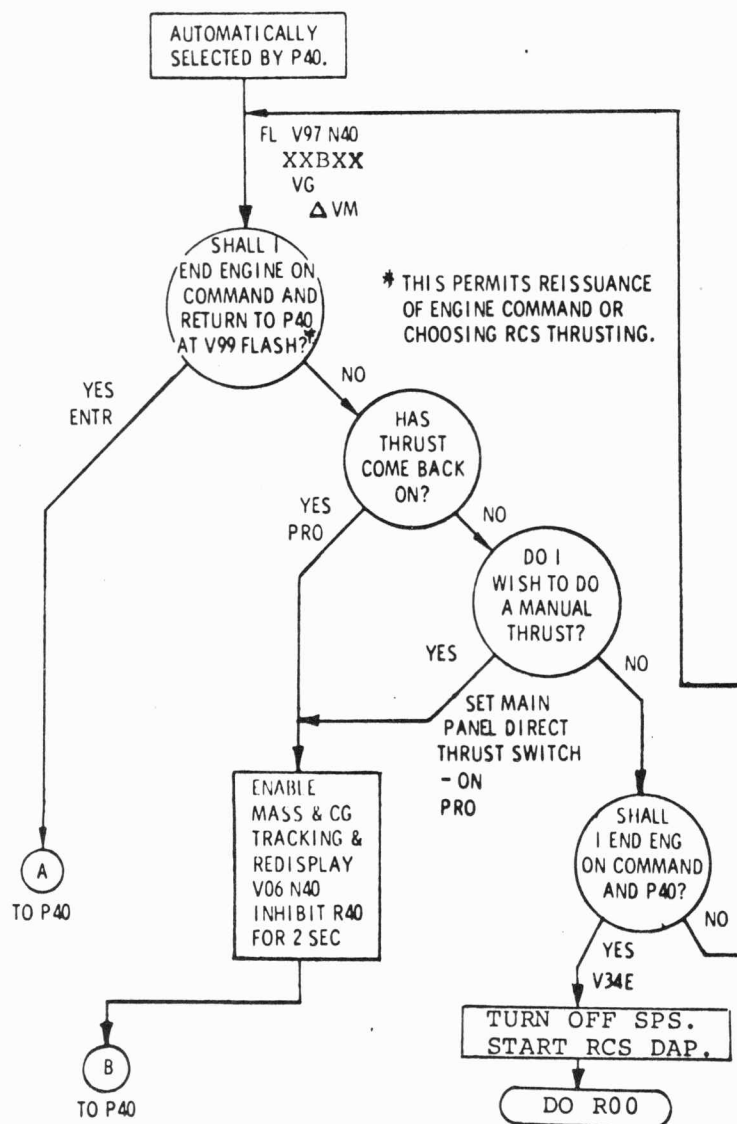


Figure 6.2.1-3. SPS Thrust Fail Routine (R40)

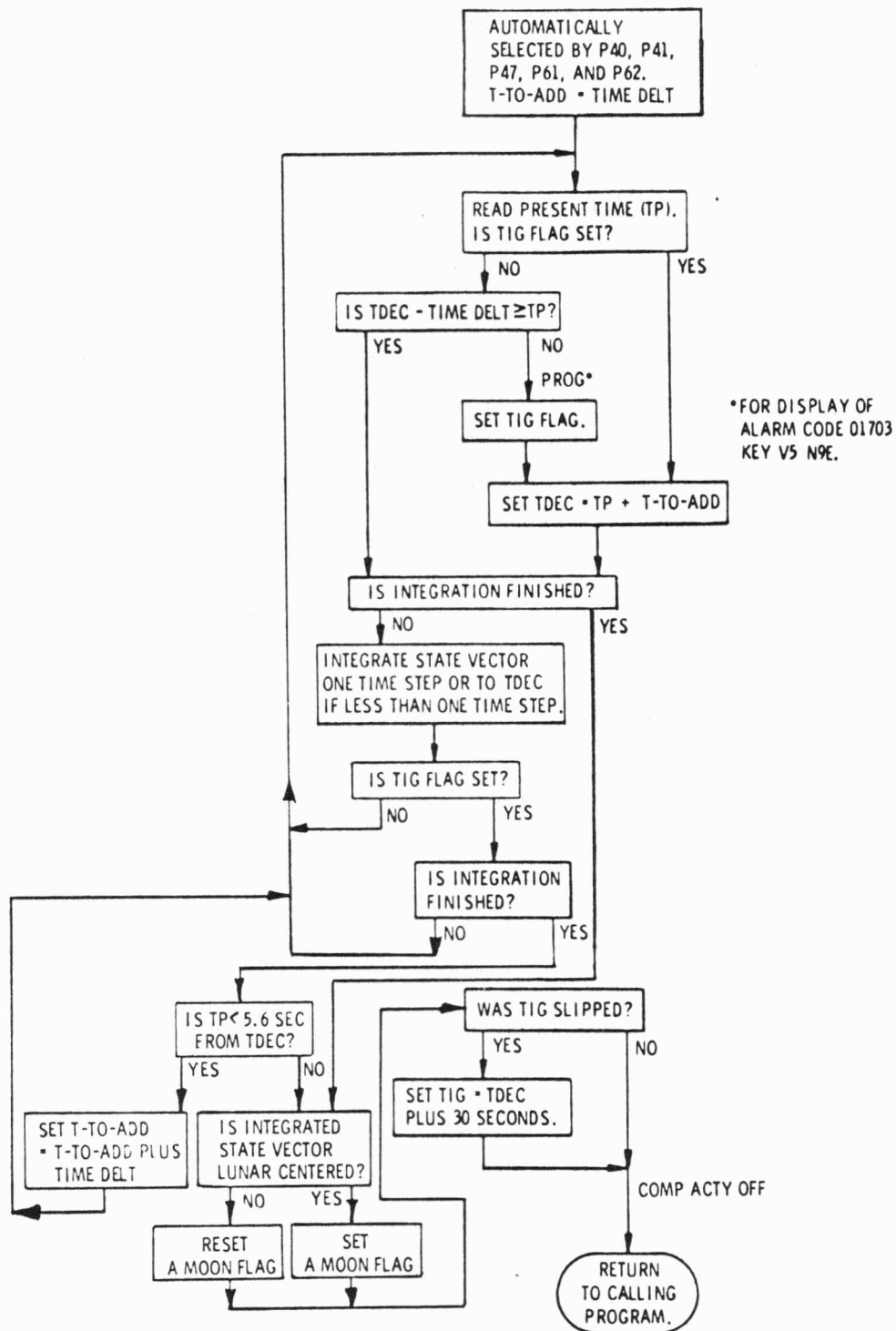


Figure 6.2.1-4. State Vector Integration Routine (R41)

Alarm codes 00210 and 00220 may occur immediately after the program is entered and the IMU Status Check Routine is called. They appear as PROG alarms on the DSKY when the crew keys VERB 05 NOUN 09 ENTR to identify the abnormality. When the alarm is identified, the crew depresses KEY REL and RSET and responds to flashing VERB 37.

Alarm code 01301 may occur during R60. After verifying the alarm, the crew selects P52 to realign the IMU and then reselects P40.

Alarm code 01407 may occur during an SPS burn, indicating that the angle between v_G and the thrust direction vector is greater than 90 deg. Crew procedures should be consulted about recovery.

Alarm code 01703 may occur during R41 of P40. After verifying the alarm, the crew will note a discontinuity in the contents of DSKY R1 (i.e., time from t_{IG}). The value on the Digital Event Timer will no longer be valid. No crew action is necessary.

6.2.1.7 Restarts

Should a restart occur during P40, the RESTART light would go on; the crew would probably not notice any other effects.

6.2.2 P41, Reaction Control System (RCS) Maneuver Program—CMC

P41, one of the powered flight guidance programs, can be used to handle the timing of short, manually controlled RCS burns whenever a change-of-orbit maneuver is required. During these burns, P41 maintains the CSM state vector, controls spacecraft attitude—to achieve the desired velocity at the end of the maneuver—and provides the crew with a monitor of the maneuver's progress.

P41 uses the AVERAGEG routine for state vector updating and the steering routines (i.e., Lambert Aimpoint or External $\Delta \underline{v}$) to compute DSKY displays. (Refer to subsection 6.1.)

The crew's first choice about a powered flight maneuver must be which of the powered flight programs to use. When a GNCS-controlled maneuver is desired, the choice of program usually depends on the magnitude of velocity-to-be-gained (i.e., on the amount of energy required to accomplish the maneuver). P41 is chosen if \underline{v}_G is less than,

$$\frac{F_{\text{SPS}}}{m} \cdot \Delta t_{\text{MIN}}$$

In the above expression, F_{SPS} is the thrust of the SPS engine (about 20,500 lb), m is the mass of the total vehicle (including the LM if it is attached), and Δt_{MIN} is the minimum burn time for which the particular SPS engine being considered has been successfully tested. Currently, Δt_{MIN} equals 0.5 sec. The maximum \underline{v}_G that can be acquired by an RCS burn (P41) can be determined by:

$$\left| \underline{v}_G \right| = \frac{\dot{w}_{\text{prop}}}{m} \cdot \text{ISP}_{\text{RCS}}$$

where \dot{w}_{prop} is the weight of RCS fuel available, and

$$\text{ISP}_{\text{RCS}} = \frac{F_{\text{RCS}}}{\dot{w}_{\text{prop}}} = 276.45 \text{ sec}$$

A prethrust program, P3x, establishes the parameters needed for thrust control guidance. After the appropriate P3x has been performed, the astronaut must not select another P3x, P7x, P17, or P23 before the burn. These programs use some of the same variable computer storage locations and would destroy the thrusting parameters established by the original P3x for this burn. Since mark incorporation would change the current state vector without correspondingly changing the thrusting parameters, P20 should not be selected between P3x and P41. If P20 had been previously selected, however, it may continue to run in the background. (The mark incorporation function is turned off by P3x.)

6.2.2.1 P41 Procedures

Tables 6.2.2-I and -II show P41 displays and extended verbs, respectively. Figure 6.2.2-1 is a flowchart of P41.

Before entering P41, the Autopilot Data Load Routine (R03) and a prethrust program (P3x) must be performed. In addition, the IMU must be powered up and aligned.

When the crew selects P41, the program computes the initial thrust direction and the preferred attitude matrix, then performs the IMU Status Check Routine (R02) and illuminates the PROG light if the ISS is off (alarm code is 00210) or if the IMU orientation is not known (alarm code is 00220).

At the completion of R02, the program enters the Attitude Maneuver Routine (R60), flashes VERB 50 NOUN 18, and displays the desired gimbal angles to 0.01 deg in the registers as follows:

R1 = OGA, roll
R2 = IGA, pitch
R3 = MGA, yaw.

The crew has the option of performing (i.e., keying PRO) or bypassing (i.e., keying ENTR) this maneuver in P41. If the PROG light goes on at this point and the alarm code is 01301, the desired gimbal angles are indeterminate because the initial \underline{v}_G is collinear with the stable member y-axis. A maneuver to the desired attitude would produce gimbal lock.

If the yaw angle is not small enough to avoid approaching gimbal lock, the crew can select P52 to do the required preferred realignment. If the yaw angle is small enough, the crew can perform the attitude maneuver automatically or manually. If

TABLE 6.2.2-1

DISPLAYS ASSOCIATED WITH P41

DSKY	Initiated by	Purpose	Condition	Register
V05 N09E	Astronaut	Verify PROG alarm	00205 Bad PIPA reading detected 00210 ISS not on 00220 IMU orientation unknown 01301 arc-sine or arc-cosine argument too large 01703 time of ignition slipped	R1 xxxxx R2 xxxxx R3 xxxxx *
FL V50 N18	R60	Display required gimbal angles	OGA - roll IGA - pitch MGA - yaw	R1 xxx. xx deg R2 xxx. xx deg R3 xxx. xx deg
V06 N18	R60	Display of final gimbal angles	OGA IGA MGA	R1 xxx. xx deg R2 xxx. xx deg R3 xxx. xx deg
FL V16 N85	P41	Display re-remaining v_G	Components of v_G	R1 xxxx. x ft/sec R2 xxxx. x ft/sec R3 xxxx. x ft/sec
FL V16 N44	Astronaut	Display orbital parameters (R30)	Apogee altitude Perigee altitude Time of free fall	R1 xxxx. x n. mi. R2 xxxx. x n. mi. R3 xx Bxx min. sec
V06 N85	P41	Display v_G	Three components of v_G to be acquired, in control coordinates	R1 xxxx. x ft/sec R2 xxxx. x ft/sec R3 xxxx. x ft/sec
FL V16 N54	R31	Display	Range Range rate Theta	R1 xxx. xx n. mi. R2 xxxx. x ft/sec R3 xxx. xx deg
V16 N62	Astronaut	Display	Velocity Rate of altitude change Altitude	R1 xxxxx. ft/sec R2 xxxxx. ft/sec R3 xxxx. x n. mi.

* The alarm codes are displayed as follows:

R1 = First alarm following error reset
R2 = Second alarm following error reset
R3 = Most recent alarm.

TABLE 6.2.2-II
EXTENDED VERBS FOR USE WITH P41

VERB	Identification	Purpose	Remarks
82 ENTR	Do R30	Compute and display relevant orbital parameters	DSKY displays apogee, perigee; and time of free fall
83 ENTR	Do R31	Display rendezvous parameters	DSKY displays range, range rate and theta, the angle between local horizontal and the spacecraft X-axis

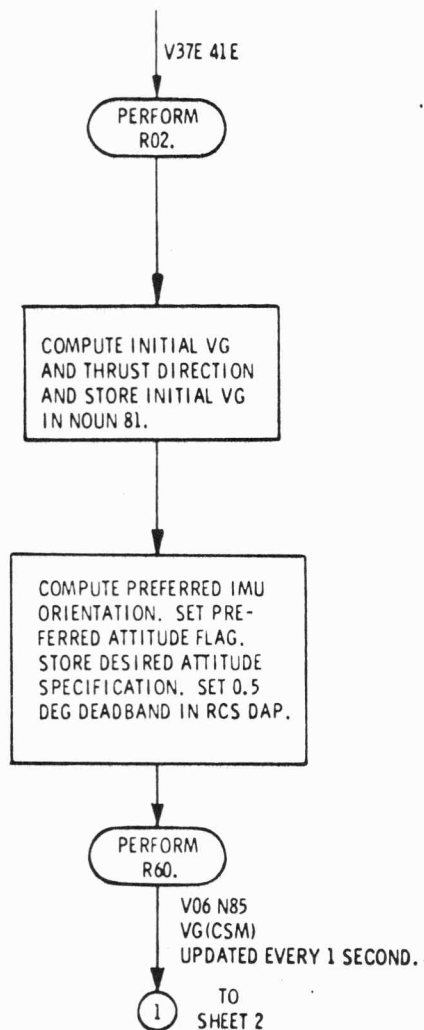


Figure 6.2.2-1. RCS Manuever Program (P41) (Sheet 1 of 2)

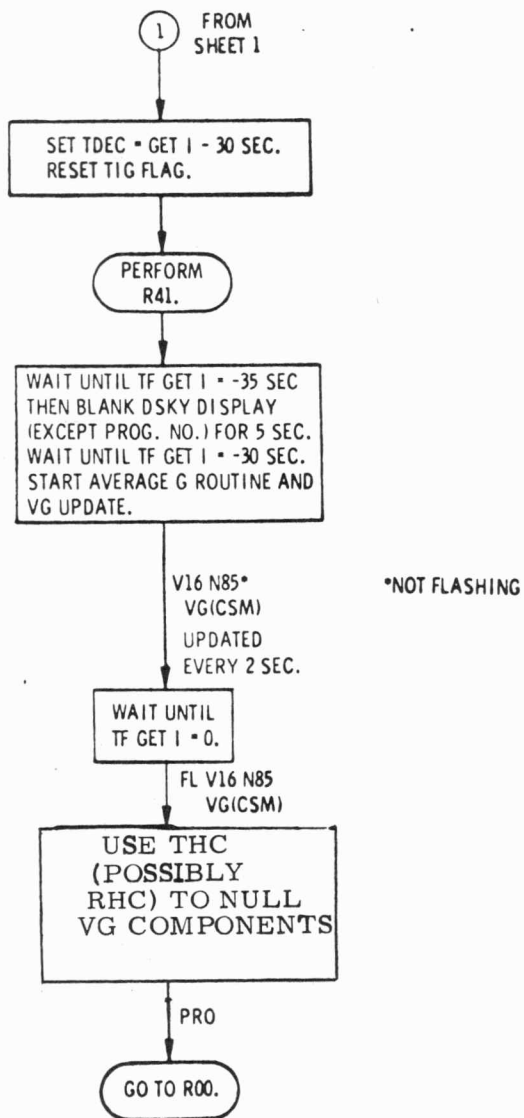


Figure 6.2.2-1. RCS Manuever Program (P41) (Sheet 2 of 2)

the maneuver is performed by the autopilot, the crew places the SC CONT switch in CMC, the CMC MODE switch in AUTO, and then keys PRO to VERB 50 NOUN 18, signaling the RCS DAP to begin the maneuver via R60.

During the maneuver, a non-flashing VERB 06 NOUN 18 displays the final gimbal angles, and the crew monitors the maneuver on the FDAI ball and needles. If gimbal lock is approached, or if the entire maneuver is done manually, the crew uses the RHC to complete the maneuver. (Once the RHC is removed from detent, the automatic maneuvering routine ceases and can be reinitiated only by keying PRO in response to the flashing VERB 50 NOUN 18.) A VERB 50 NOUN 18 display occurs upon completion of the R60 maneuver. To exit from R60, the crew keys ENTR in response to VERB 50 NOUN 18.

Upon completion (or termination) of R60, the DSKY displays (and repeats every second) VERB 06 NOUN 85; the three registers contain the three components of \underline{v}_G , in control coordinates. The total velocity to be acquired during the maneuver is displayed and decreases when the maneuver begins. Nominally, the crew places SC CONT in CMC and CMC MODE in AUTO or HOLD.

The program at this time enters the State Vector Integration Routine (R41) which integrates the CSM state vector ahead to $t_{IG}-30$ seconds. If R41 cannot be completed before $t_{IG}-42.5$, a program alarm (code 01703) is generated and the time of ignition is slipped. R41 is explained in more detail in paragraph 6.2.1.5.2.

At $t_{IG}-35$, the DSKY is blanked for 5 seconds, then the VERB 16 NOUN 85 display will start to monitor the same register data. If \underline{v}_G updating is being executed in the External $\Delta \underline{y}$ mode, a change of more than 0.4 ft/sec in any component during the period $t_{IG}-30$ to t_{IG} indicates excessive PIPA bias.

At t_{IG} , the program flashes VERB 16 NOUN 85. The crew, using the RHC and THC, should null the velocity-to-be-gained to a value specified in the checklist. Upon completion of thrusting, the crew keys PRO to end major mode P41.

The crew may select the Orbital Parameters Display (VERB 82 ENTR) to check apogee altitude, perigee altitude, and time of free-fall. If R2—showing perigee altitude—is greater than 49.4 n. mi. (near earth) or 5.8 n. mi. (near the moon), R3—showing time of free-fall—should read 59 minutes 59 seconds. The crew keys PRO to return to the flashing VERB 37 display.

The crew can key VERB 83 ENTR to monitor the range, range rate, and the angle between local horizontal and the spacecraft X-axis. To monitor the velocity, rate of altitude change (HDOT), and altitude (H), the crew can key VERB 16 NOUN 62.

AVERAGEG will continue running until a new major mode is selected. Therefore, immediate new-mode selection is imperative to avoid accumulation of PIPA bias errors.

6.2.2.2 Time Lines

The time lines shown in Figure 6.2.2-2 relate the program flowchart to crew observance and response.

6.2.2.3 Alarms

The alarm codes which may occur in P41 are listed below and a detailed explanation of each follows:

- a. Alarm code 00205 occurs when a bad PIPA reading is detected.
- b. Alarm code 00210 occurs if the ISS is not on.
- c. Alarm code 00220 occurs if the IMU orientation is not known.
- d. Alarm code 01301 occurs if the arc-sine or arc-cosine argument is too large.
- e. Alarm code 01703 occurs if the time of ignition is slipped.

Alarm code 00205 may occur during the thrusting maneuver. The maneuver should then probably be terminated since the display and AVERAGEG state vector maintenance will no longer be valid.

Alarm code 01301 may occur during R60. After verifying the alarm (i.e., keying in VERB 05 NOUN 09 ENTR) the crew should select P52 to realign the IMU. Then P41 may be reselected.

For a detailed explanation of the occurrence of alarm codes 00210 and 00220 and 01703, refer to paragraph 6.2.1.6.

6.2.2.4 Restarts

Should a restart occur during P41, the RESTART light on the DSKY will be illuminated. No other effects will be noticed by the crew.

COMPUTER PERFORMANCE

ASTRONAUT/DSKY

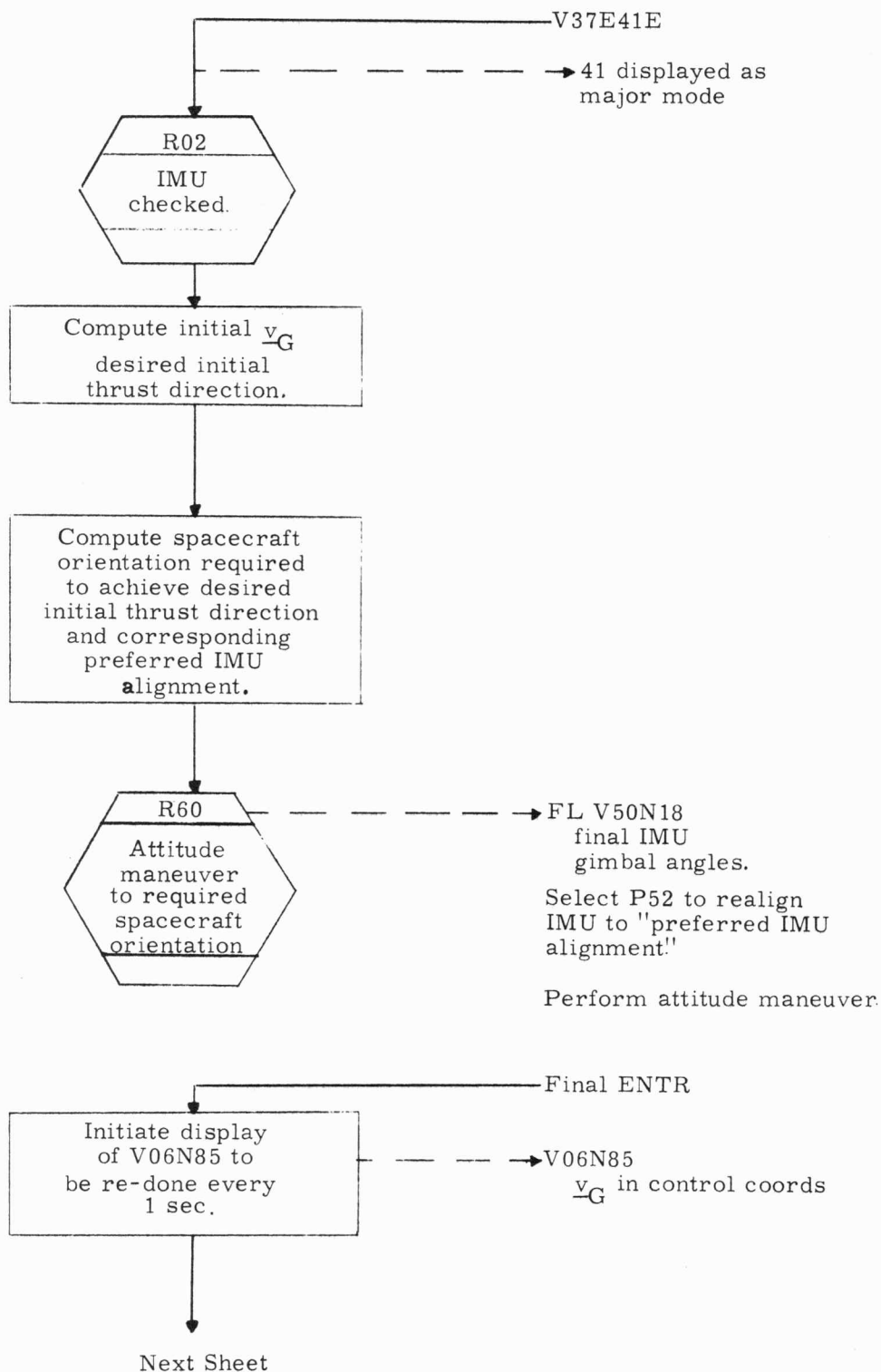


Figure 6.2.2-2. Time Lines of RCS Maneuver Program (P41) (Sheet 1 of 2)

COMPUTER PERFORMANCE

ASTRONAUT/DSKY

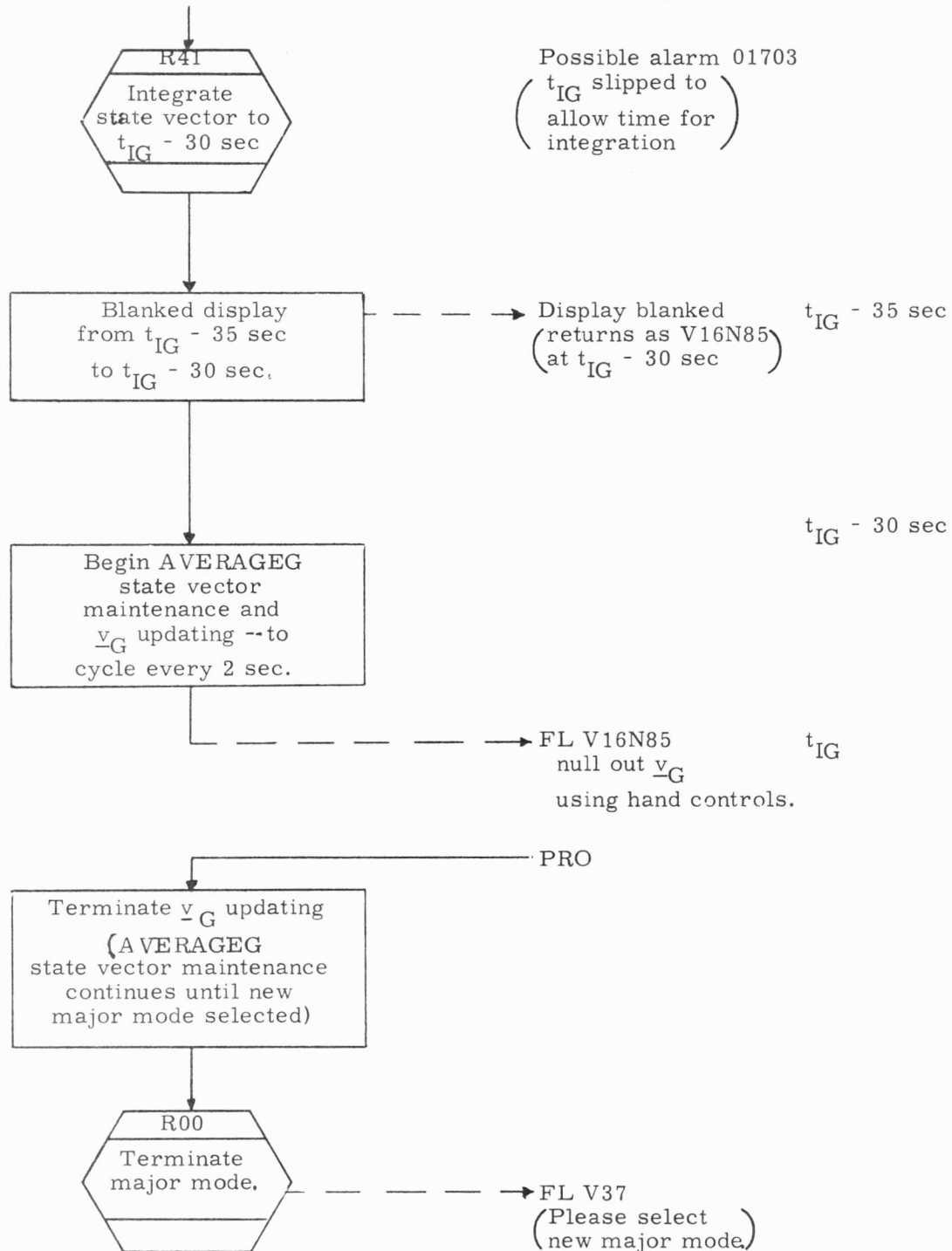


Figure 6.2.2-2. Time Lines of RCS Maneuver Program (P41) (Sheet 2 of 2)

6.2.3 P47, Thrust Monitor Program—CMC

P47, the powered flight monitor program, maintains the CSM state vector during a thrusting maneuver not controlled by the GNCS and provides a monitor of the maneuver's progress for the crew. For example, the trans-lunar insertion (TLI) maneuver is done using the SIVB; the final docking maneuver in rendezvous is done using THC manual control; in case of an SPS engine failure during the second lunar orbit insertion (LOI2) maneuver, or late in the first lunar orbit insertion (LOI1) maneuver (when enough fuel has been used to make a sufficiently light vehicle), the LM DPS or APS engine can be used to initiate a return to earth.

The program uses the AVERAGEG routine for state vector updating. (For an explanation of AVERAGEG use, refer to subsection 6.1.)

6.2.3.1 P47 Procedures

Tables 6.2.3-I and -II present the displays and extended verbs associated with P47. Figure 6.2.3-1 is the program flowchart. Before entering P47, the CMC and the IMU must be on and aligned.

Upon selection of P47, shortly before t_{IG} , the program performs the IMU Status Check Routine (R02) and illuminates the PROG light if the ISS is off (i.e., alarm code is 00210) or the IMU orientation is unknown (alarm code is 00220).

At the completion of R02, the program enters the State Vector Integration Routine (R41), which integrates the CSM state vector ahead to a specified number of seconds (ϵ) from the present. In ϵ seconds, the AVERAGEG cycle begins. (Refer to paragraph 6.2.1.5.2 for a description of R41.)

The DSKY displays a flashing VERB 16 NOUN 83 with the three components of acquired Δy , in control coordinates. The registers contain zeros initially; the contents are updated every 2 seconds.

While the thrusting maneuver is performed, the crew must monitor the FDAI ball to avoid gimbal lock. If the PROG light goes on during the maneuver, the occurrence of an alarm code 00205 indicates the detection of a bad PIPA reading. If the crew wishes to recycle the display (zeroing the registers), VERB 32 ENTR can be keyed.

To terminate major mode P47, the crew keys PRO. The DSKY then flashes VERB 37, requesting the selection of a new major mode. It is important to respond to

TABLE 6.2.3-1

DISPLAYS ASSOCIATED WITH P47

DSKY	Initiated by	Purpose	Condition	Register
V05 N09E	Astronaut	Verify PROG alarm	00205 Bad PIPA reading detected 00210 ISS not on 00220 IMU orientation unknown	R1 xxxxx R2 xxxxx R3 xxxxx*
FL V16 N83	P47	Display Δy acquired	Three components in control coordinates	R1 xxxx. x ft/sec R2 xxxx. x ft/sec R3 xxxx. x ft/sec
FL V16 N44	Astronaut	Display orbital parameters (R30)	Apogee altitude Perigee altitude Time of free fall	R1 xxxx. x n. mi. R2 xxxx. x n. mi. R3 xxBxx min, sec
FL V16 N54	R31	Display	Range Range rate Theta	R1 xxx. xx n. mi. R2 xxxx. x ft/sec R3 xxx. xx deg
FL V16 N53	R34	Display	Range Range rate Phi	R1 xxx. xx n. mi. R2 xxxx. x ft/sec R3 xxx. xx deg
V16 N62	Astronaut	Display	Velocity Rate of altitude change Altitude	R1 xxxxx. ft/sec R2 xxxxx. ft/sec R3 xxxx. x n. mi.

* The alarm codes are displayed as follows:

- R1 = First alarm following error reset
- R2 = Second alarm following error reset
- R3 = Most recent alarm

TABLE 6.2.3-II

EXTENDED VERBS FOR USE WITH P47

VERB	Identification	Purpose	Remarks
82 ENTR	Do R30	Compute and display relevant orbital parameters	DSKY displays apogee, perigee; and time of free fall
83 ENTR	Do R31	Display first set of rendezvous parameters	DSKY displays range, range rate and theta, the angle between local horizontal and the spacecraft X-axis
85 ENTR	Do R34	Display second set of rendezvous parameters	DSKY displays range, range rate and phi, the angle between local horizontal and the sextant SLOS

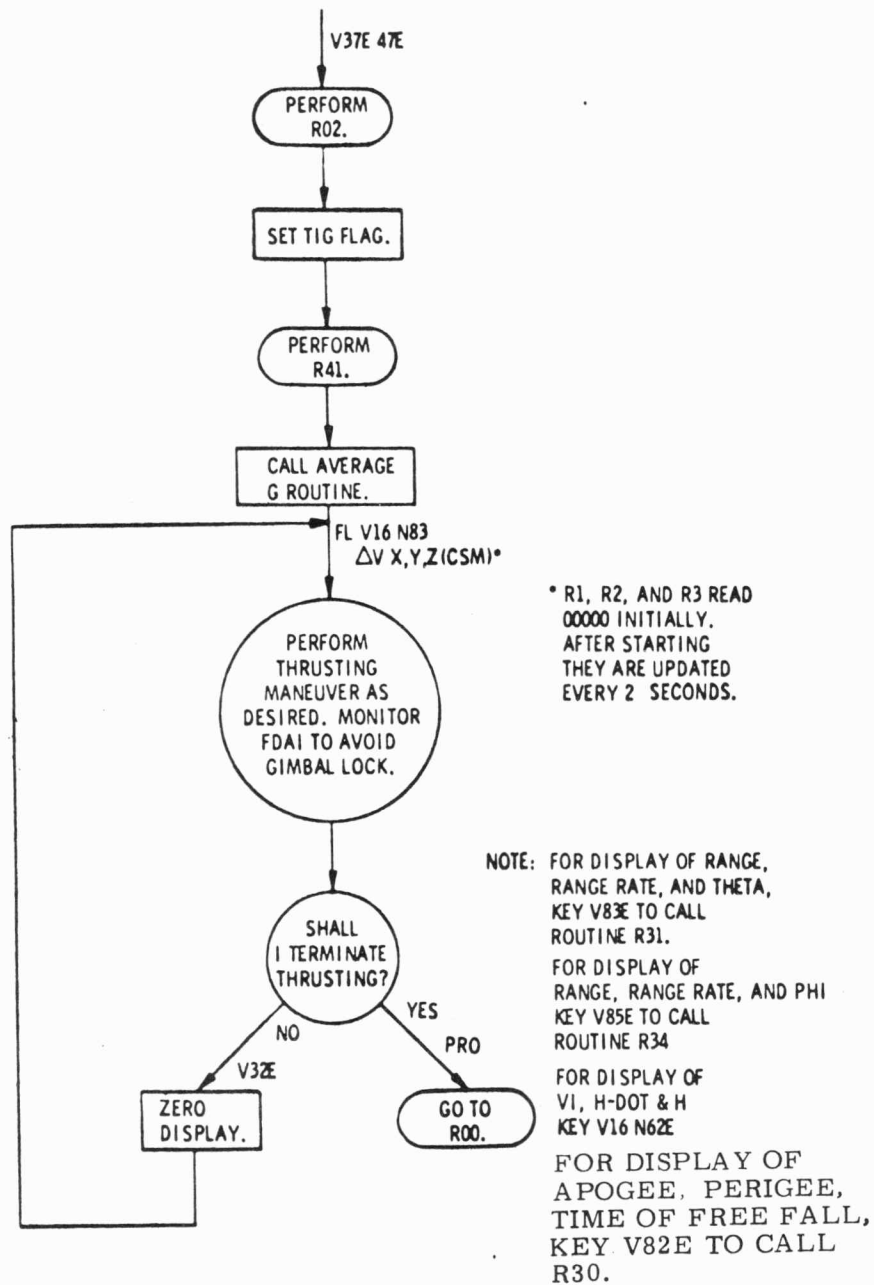


Figure 6.2.3-1. Thrust Monitor Program (P47)

this immediately to terminate AVERAGEG and thus avoid accumulation of PIPA bias errors.

6.2.3.2 Time Lines

The time lines shown in Figure 6.2.3-2 relate the program flowchart to crew observance and response.

6.2.3.3 Alarms

The PROG alarm codes associated with P47 are listed below. A detailed description of each follows.

- a. Alarm code 00205 occurs if a bad PIPA reading is detected.
- b. Alarm code 00210 occurs if the ISS is not on.
- c. Alarm code 00220 occurs if the IMU orientation is not known.

Alarm code 00205 may occur during the thrusting maneuver. The maneuver should be terminated since the display and AVERAGEG state vector maintenance will no longer be valid.

For detailed explanations of alarm codes 00210 and 00220, refer to paragraph 6.2.1.6.

6.2.3.4 Restarts

Should a computer restart occur, the RESTART light DSKY would be illuminated; no other effect would be noticed by the crew.

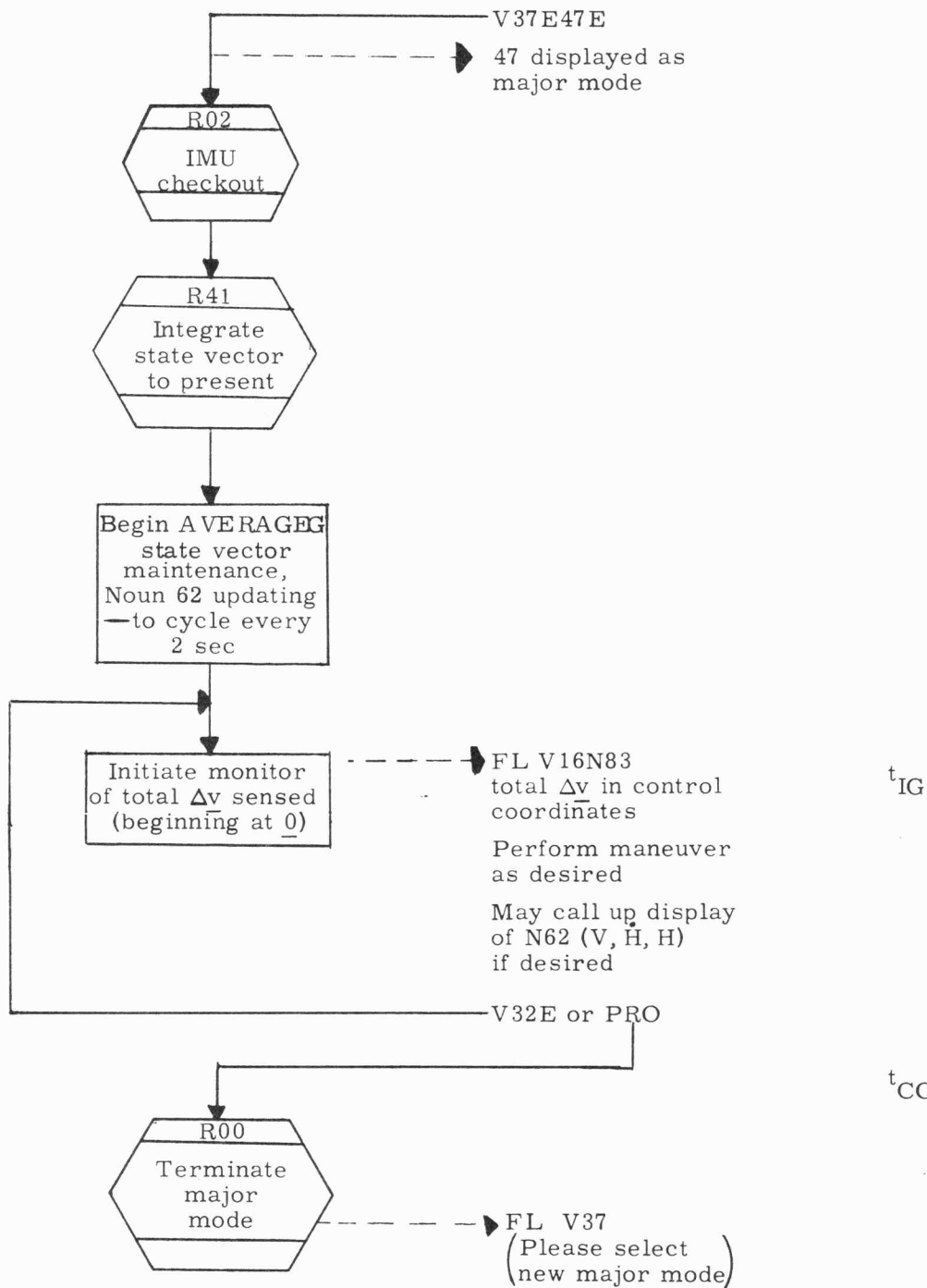


Figure 6.2.3-2. Time Lines of Thrust Monitor (P47)

7.3.3 P57, Lunar Surface Alignment Program

P57 provides the crew with the capability to align or realign the IMU while the LM is on the lunar surface, using one of three types of orientation: (1) preferred (2) landing site (3) REFSMMAT. Within each of these types of orientation are four techniques available to the crew for completing the IMU alignment. The techniques are identified as 0 through 3 and are described below. If the alignment technique selected is other than 0, the program is designed to perform an initial alignment using the vectors of technique 0. After this initial alignment is completed, the program automatically recycles to perform the IMU realignment using the technique specified by the crew. Information obtained from the alignment is displayed via the DSKY to the crew and includes such data as the following:

- a. Type of alignment
- b. Time of alignment
- c. Lunar gravity vector error angle
- d. Position, including detent, azimuth, and elevation of the Alignment Optical Telescope when sighting celestial bodies
- e. Gyro and gimbal angles
- f. Landing site coordinates.

The displays associated with P57 are shown in Table 7.3.3-1.

7.3.3.1 Related Routines

Three routines are directly related to the Lunar Surface Alignment Program and are all called automatically by the program. One of the directly related routines calls an additional routine; this routine in turn calls another routine. Thus, P57 actually has the following five related routines:

- a. AOT Mark Routine (R53)
- b. Sighting Data Display Routine (R54)
- c. Markrupt Routine (R57)
- d. Celestial Body Definition Routine (R58)
- e. Lunar Surface Sighting Mark Routine (R59).

When using P57 techniques 2 or 3 (refer to paragraph 7.3.3.3), optical sightings on a celestial body (navigation star, planet, or sun) are required. The Lunar Surface Sighting Mark Routine (R59) performs AOT sightings on these celestial bodies. R59 then automatically calls the AOT Mark Routine (R53) to process the sighting

TABLE 7.3.3-I
PROGRAM DISPLAYS (SHEET 1 OF 2)

DSKY	Initiated By	Purpose	Condition	Register
FL V04 N06	P57	Option code for assumed IMU orientation selection	Option code ID (R1) Option code (R2) X = 1 = Preferred 2 = Nominal 3 = REFSMMAT 4 = Landing site	R1 00001 R2 0000x R3 Blank
FL V06 N34	P57	Time at which the LM position vector is defined for a landing site orientation	T (Align)	R1 00xxx hr R2 000xx min R3 0xx.xx sec
FL V05 N06	P57	Option code for assumed alignment technique	Option code ID (R1) Option code (R2) Stored data code (R3) C = 1 REFSMMAT defined C = 0 No REFSMMAT defined D = 1 LM attitude available D = 0 LM attitude not available	R1 00010 R2 0000x R3 00CD0
FL V06 N04	P57	Gravity error angle	GRAV ERR ANGLE (difference between present and previously defined error angle.)	R1 xxx.xx deg R2 Blank R3 Blank
FL V01 N70	R59	AOT detent code and star code	AOT detent/star code A, B = 00 C = detent 1 = left 2 = center 3 = right 4 = right rear 5 = center rear 6 = left rear 7 = back-up optical system (not used on lunar surface) D, E, star code:00 planet; 01/45 star; 46, 47, 50, Sun, Earth Moon, respectively	R1 ABCDE (Octal) R2 Blank R3 Blank

TABLE 7. 3. 3-1
PROGRAM DISPLAYS (SHEET 2 OF 2)

DSKY	Initiated By	Purpose	Condition	Register
FL V06 N79	R59	Cursor and spiral angle, and AOT position code	Cursor angle Spiral angle Position code 1, 2, 3 = forward positions 4, 5, 6 = rear positions	R1 xxx. xx deg R2 xxx. xx deg R3 xxxxx.
FL V01 N71	R53	AOT detent/star code	AOT detent and star code (same as N70 above)	R1 ABCDE R2 Blank R3 Blank
FL V06 N87	R53	Back-up optical system azimuth and elevation LOS	Option azimuth Option elevation	R1 xxx. xx deg R2 xxx. xx deg R3 Blank
FL V54 N71	R53	Mark X or Y reticle line/star intersection	Mark X and/or Y reticle/star intersection (same as N71 above)	R1 ABCDE R2 Blank R3 Blank
FL V06 N88	R58	Assumed planet position	XPL 1/2 unit YPL Position vector ZPL Components	R1 . xxxxx R2 . xxxxx R3 . xxxxx
FL V06 N05	R54	Sighting angle difference	Sighting angle difference = measured minus catalog values	R1 xxx. xx deg R2 Blank R3 Blank
FL V06 N93	P57	Gyro torquing angles	X Gyro angle Y Gyro angle Z Gyro angle	R1 xx. xxx deg R2 xx. xxx deg R3 xx. xxx deg
FL V06 N22	P57	Resulting ICDU gimbal angles	OG IG MG	R1 xxx. xx deg R2 xxx. xx deg R3 xxx. xx deg
FL V50 N25	P57	Please perform fine align	Option code 00014 = fine align	R1 00014 R2 Blank R3 Blank
FL V06 N89	P57	Landing site coordinates	LAT LONG/2 ALT	R1 xx. xxx deg R2 xx. xxx deg R3 xxx. xx n. mi.

marks taken by the crew. However, in order for the crew to load the spiral and cursor angles while taking marks, R53 calls a portion of the Markrupt Routine (R57). With the processed information from R53, the Celestial Body Definition Routine (R58) then establishes the planet position vectors for the celestial body being used for the IMU alignment. P57 then transforms the LOS vectors in reference coordinates into desired IMU coordinates, calls the Sighting Data Display Routine (R54) that calculates the difference between the actual (stored) and the indicated (measured) sighting angles, and displays this information to the crew. The crew then decides whether to continue with the alignment using the available information or to take new sighting information and start the alignment process again.

7.3.3.2.1 Basic Reference Coordinate System.—The Basic Coordinate System is an orthogonal inertial coordinate system whose origin is located at either the moon's or earth's center of mass; its orientation is defined as the line of intersection of the mean earth equatorial plane and the plane defined by the mean orbit of the earth (ecliptic) at a specified time. The X-axis is along this line of intersection with the positive sense in the direction of the ascending node of the ecliptic at the equator; the Z-axis is along the mean earth North pole; and the Y-axis completes the right hand triad.

This coordinate system becomes moon-centered when the estimated vehicle distance from the moon first falls below approximately 38000 miles. This coordinate system again becomes earth-centered when the distance to the moon first exceeds this value. All navigation stars and lunar-solar ephemerides are referenced to this coordinate system, as are all state vectors and stable member orientations.

7.3.3.2.2 IMU Stable Member Coordinate System.—The IMU stable member coordinate system depends on the current IMU alignment. The origin of the IMU stable member coordinate system is the center of the IMU stable member. The primary alignment orientations used in P57 are as follows:

a. Preferred Alignment

$$\begin{aligned} \underline{u}_{XSM} &= \underline{u}_{TD} \\ \underline{u}_{YSM} &= \text{UNIT} (\underline{u}_{XSM} \times \underline{r}) \text{ If } \underline{r} \text{ not parallel to } \underline{u}_{TD} \\ \text{or} &= \text{UNIT} (\underline{u}_{XSM} \times \underline{v}) \text{ If } \underline{r} \text{ parallel to } \underline{u}_{TD} \\ \underline{u}_{ZSM} &= \underline{u}_{XSM} \times \underline{u}_{YSM} \\ \text{where } \underline{u}_{TD} &= \text{unit vector in desired thrust direction at ignition} \\ \underline{r} &= \text{position vector at ignition} \\ \underline{v} &= \text{velocity vector at ignition} \end{aligned}$$

b. Local Vertical

$$\underline{u}_{XSM} = \text{UNIT}(\underline{r}) \text{ at } t_{\text{align}}$$

$$\underline{u}_{YSM} = \text{UNIT}(\underline{v} \times \underline{r})$$

$$\underline{u}_{ZSM} = \underline{u}_{XSM} \times \underline{u}_{YSM}$$

where \underline{r} and \underline{v} represent the vehicle state at alignment time (t_{align})

c. Lunar Landing

$$\underline{u}_{XSM} = \text{UNIT}(\underline{r}_{LS}) \text{ at } t_L$$

$$\underline{u}_{ZSM} = \text{UNIT}[(\underline{r}_C \times \underline{v}_C) \times \underline{u}_{XSM}]$$

$$\underline{u}_{YSM} = \underline{u}_{ZSM} \times \underline{u}_{XSM}$$

where \underline{r}_{LS} = lunar landing site vector at predicted landing time (t_L), \underline{r}_C and \underline{v}_C are CSM position and velocity vectors as maintained by the LGC.

d. Lunar Launch Time

Same as c except \underline{r}_{LS} is the launch site vector at launch time (t_L).

7.3.3.3 Techniques

7.3.3.3.1 Technique 0.—This technique is a quick means for alignment in case of emergency launch. The IMU is driven to the desired orientation using the present LM attitude. Either the ATTITUDE flag or REFSMMAT flag, or both, must be set. A 00701 alarm occurs if neither is set.

7.3.3.3.2 Technique 1.—This technique is selected by the astronaut whenever a complete alignment or realignment is to be made by using the computed lunar gravity vector and the present LM attitude data. A 00701 alarm occurs if neither ATTITUDE flag nor REFSMMAT flag is set. Both flags may be set.

7.3.3.3.3 Technique 2.—This technique is selected by the astronaut whenever a complete alignment or realignment is to be made by sighting on two celestial bodies (usually stars) with the AOT. It is not necessary for either the ATTITUDE flag or REFSMMAT flag to be set.

7.3.3.3.4 Technique 3.—This technique is selected when a complete alignment or realignment is to be made by determining the lunar gravity vector with the IMU accelerometers and sighting on one celestial body with the AOT. It is not necessary for either the ATTITUDE flag or the REFSMMAT flag to be set.

7.3.3.4 P57 Logical Flow Description

Several techniques are available to the crew for completing the alignment of the IMU based either on landing site orientation, preferred orientation, or REFSMMAT as described in paragraph 7.3.3.3. The resultant accuracy of the IMU to the specified orientation depends on the technique that the crew selects. This selection is dictated by the circumstances at the time of alignment. The program description that follows is based on these techniques, 0 through 3, respectively.

The crew selects P57 by keying VERB 37 ENTR 57 ENTR into the DSKY. (See Figure 7.3.3-1.) The program immediately checks to determine if the inertial subsystem (ISS) is on. If the ISS is not on, the PROG alarm light goes on. By keying VERB 05 NOUN 09 ENTR into the DSKY, the crew may determine a 00210 alarm code indication. (Refer to paragraph 7.3.3.5.) If the ISS is on and operational, the crew sees a flashing VERB 04 NOUN 06 on the DSKY with registers 1 (R1) and 2 (R2) reading 00001 and 00003, respectively. The 00001 in R1 indicates that R2 specifies the assumed IMU orientation option. The 00003 in R2 indicates that the assumed option is REFSMMAT. If this option is not the one desired by the crew, VERB 22 ENTR may be keyed into the DSKY and another option selected. (See Table 7.3.3-I.) The nominal option (00002) is not allowed in P57.

If the orientation option is preferred (00001), REFSMMAT (00003), or landing site (00004), the technique of alignment must be determined. If the orientation option is 00004, however, the time of alignment t_{ALIGN} must also be determined prior to determination of technique of alignment; t_{ALIGN} is equal to the ascent time of ignition, $t_{IG(AS)}$. If all three registers contain zeros when t_{ALIGN} is displayed, the landing site orientation will be defined for a t_{ALIGN} automatically selected by the LGC as being the present time. Regardless of the value of t_{ALIGN} , it is used to compute the landing site orientation. Upon completion of this computation and storage of its value, the previously-stored preferred orientation is lost.

The next display that the crew sees is a flashing VERB 05 NOUN 06, which displays the assumed alignment technique, the assumed alignment technique option code, and a data code in registers R1, R2, and R3, respectively. (See Table 7.3.3-I.) This display requires that the crew either key in PRO or key in the desired alignment technique by keying in VERB 22 ENTR and loading the desired code in R2.

7.3.3.4.1 Technique 0.—As stated in paragraph 7.3.3.3, if technique 0 alignment is desired, either the REFSMMAT flag or the ATTITUDE flag or, both, must be set. If just the REFSMMAT flag is set, the LM attitude in moon-fixed coordinates is

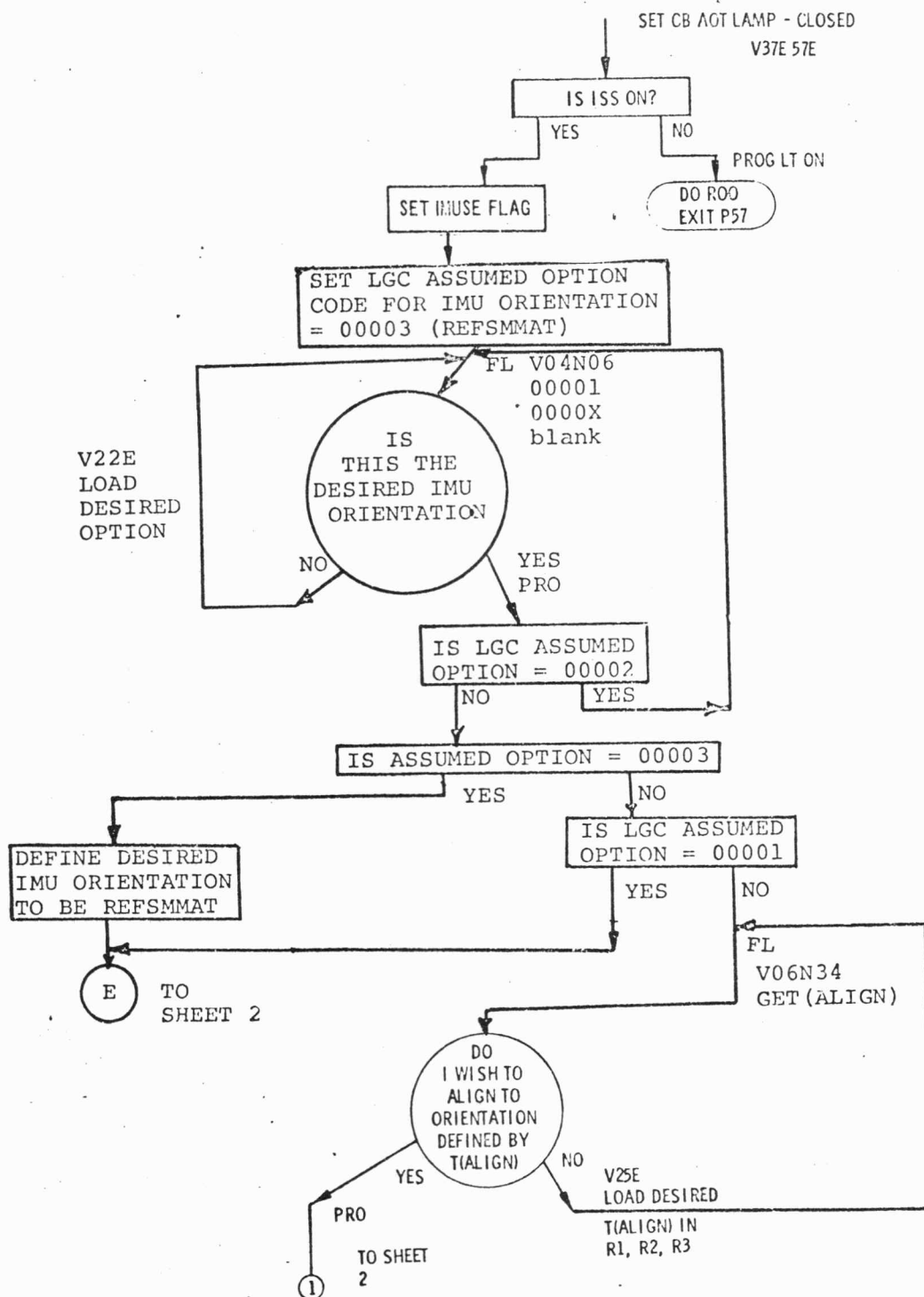


Figure 7.3.3 -1. Lunar Surface Alignment Program (P57) (Sheet 1 of 5)

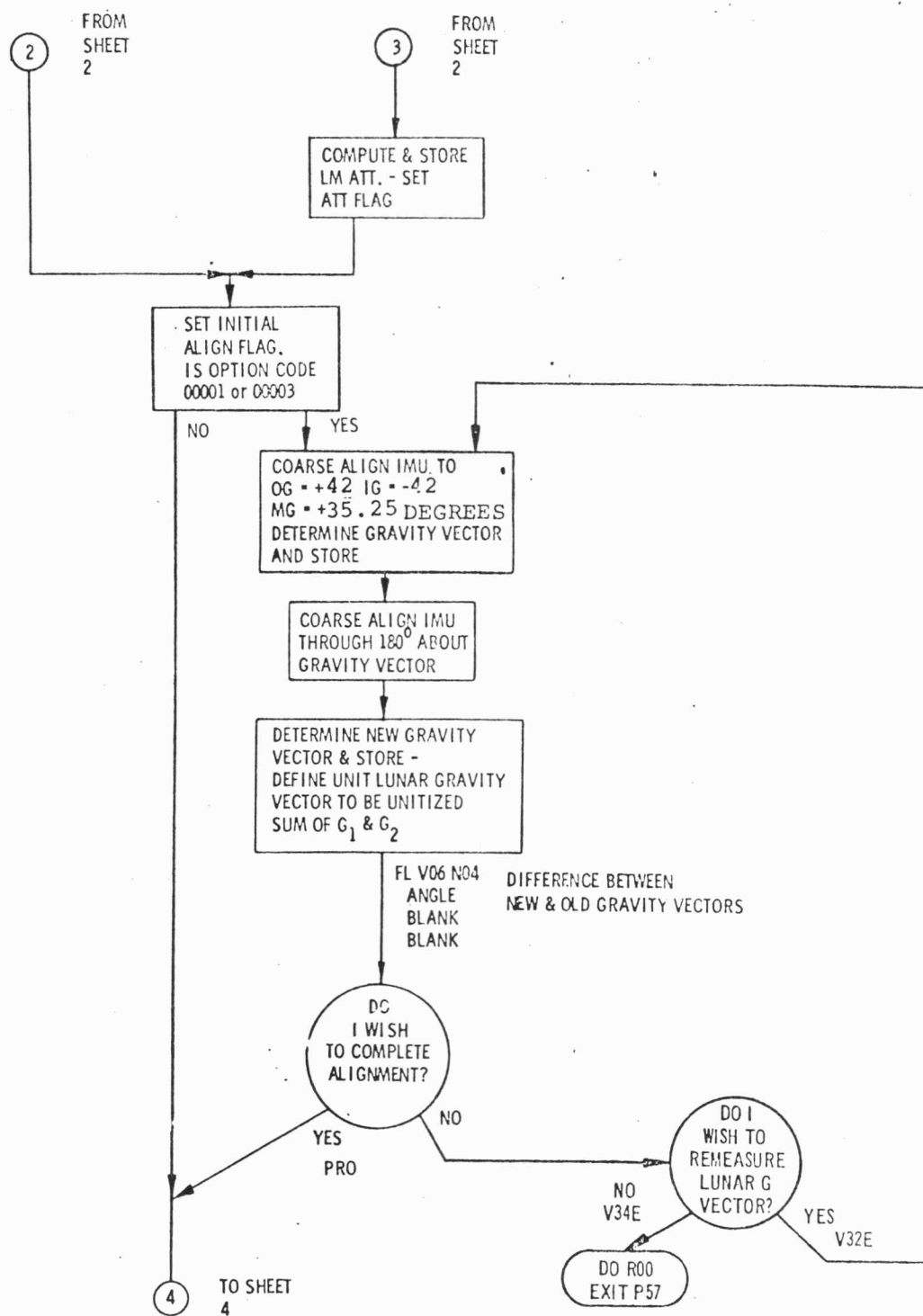


Figure 7.3.3-1. Lunar Surface Alignment Program (P57) (Sheet 3 of 5)

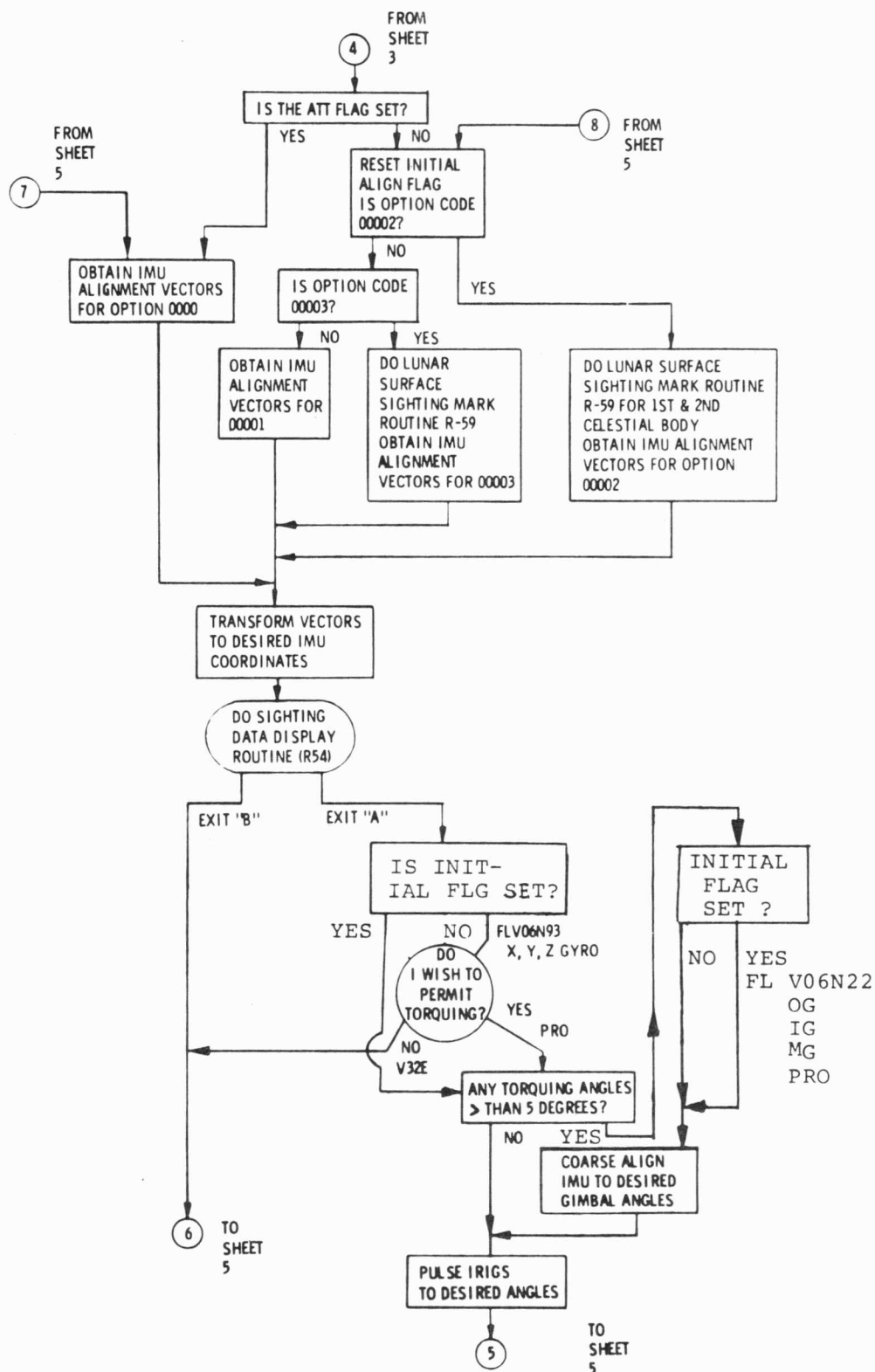


Figure 7.3.3-1. Lunar Surface Alignment Program (P57) (Sheet 4 of 5)

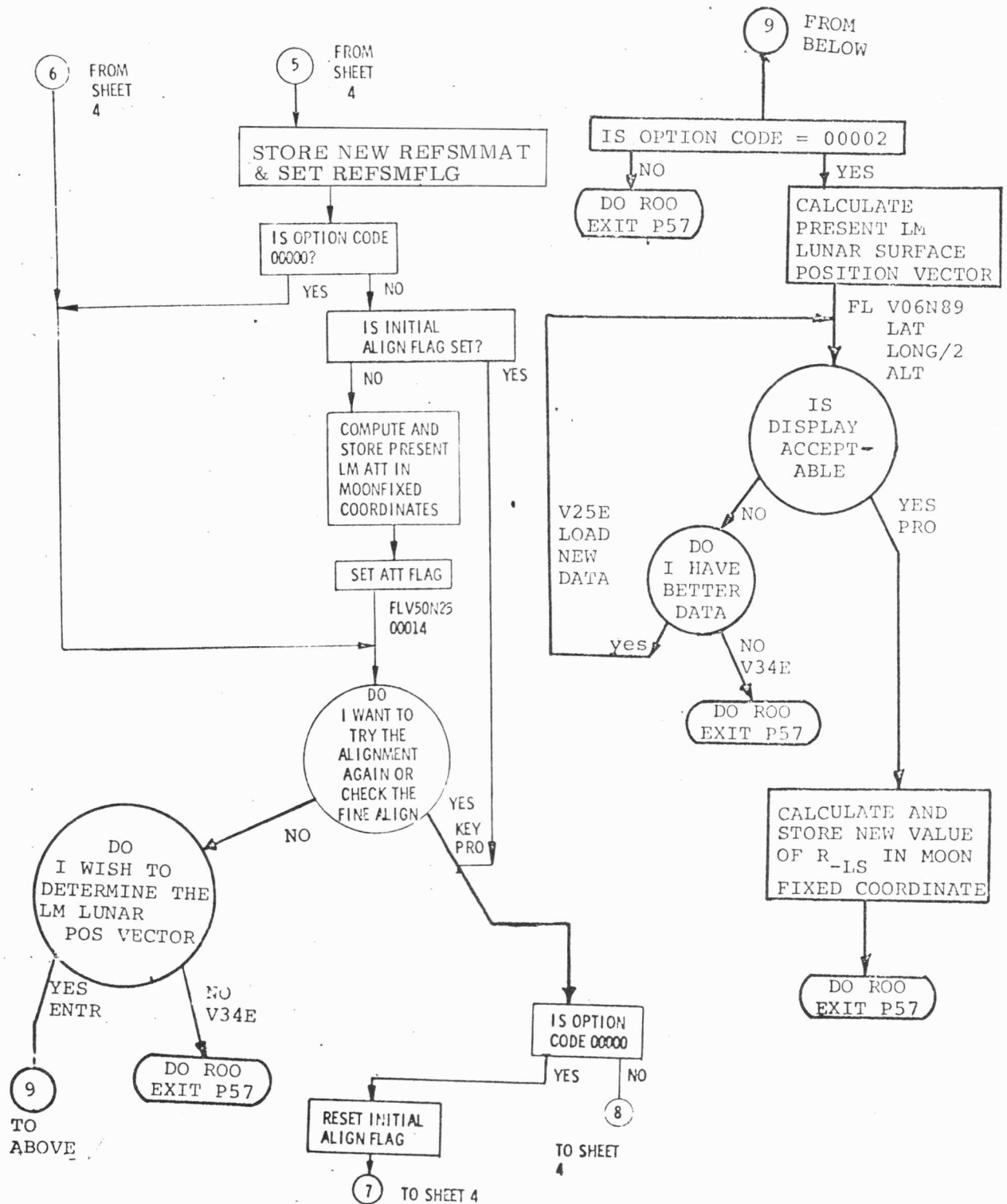


Figure 7.3.3-1. Lunar Surface Alignment Program (P57) (Sheet 5 of 5)

computed and stored by using REFSMMAT. Then the ATTITUDE flag is set. If just the ATTITUDE flag is set, it is not necessary to compute the LM attitude in moon-fixed coordinates. This sequence is common to all four alignment techniques. If the technique is other than 0, however, the INITIAL ALIGN flag is reset. After setting the ATTITUDE flag, the INITIAL ALIGN flag is set, and the unit LOS vectors are defined. (Refer to Table 7.3.3-II for source of vectors used in technique 0.)

The four IMU alignment vectors (S_A , S_B , S'_A , S'_B), are obtained as follows. The stored LM attitude vectors (Y and Z) are transformed from the moon-fixed coordinate system (MFCS) to basic reference coordinates and are defined as S'_A , S'_B , respectively. The Y and Z navigation base unit vectors define the orientation of the Y and Z LM axes with respect to the IMU stable member coordinate system and are denoted as S_A and S_B , respectively. Vectors S'_A and S'_B are then transformed from reference coordinates to desired IMU coordinates. The desired gyro-torquing angles are computed, and a check is made to determine if any of these angles are greater than 5 degrees. If not, the gyros are pulsed through the desired angles to align the IMU, and the REFSMMAT is defined to be the desired IMU orientation. A flashing VERB 50 NOUN 25 display then requests the performance of a fine alignment (code 00014). If the crew does not wish to fine align, the program may be terminated by keying in ENTR or VERB 34 ENTR, the normal exit from technique 0.

7.3.3.4.2 Technique 1.—The IMU is aligned to the desired orientation defined by the previous t_{ALIGN} display using the present REFSMMAT (or a stored LM attitude with respect to the lunar surface) and determination of the lunar gravity vector.

The LM attitude is computed and stored in moon-fixed coordinates as in technique 0. The gravity vector is then determined in the following way. The desired gimbal angles are set to +42 degrees, -42 degrees, and +35.25 degrees (OG, IG, and MG respectively), and the inertial subsystem is coarse aligned. The NO ATT light will be on indicating that the IMU is in the coarse align mode. The TRACK flag, DRIFT flag, and REFSMMAT flag are all reset. At the completion of the coarse alignment, if the gimbals are not within 2 degrees of the desired values, the PROG alarm light will come on. (Refer to paragraph 7.3.3.5, alarms 00211 and 00217.) If the system did coarse align correctly, the NO ATT light will go off indicating that the ISS is now inertial. The accelerometer outputs are monitored for approximately 40 seconds giving a gravity vector in stable member coordinates. These are unitized and transformed into navigation base coordinates, and a 1/2-unit gravity vector is stored. The gimbal angles to rotate the stable member 180 degrees are calculated, the ISS coarse aligned to these angles, and the 1/2-unit gravity vector is determined and stored as above. A flashing VERB 06 NOUN 04 will display the error between the

TABLE 7.3.3-II
SOURCES OF IMU ALIGNMENT VECTORS IN P57

Alignment Technique	Sources of IMU Alignment Vector			
	Basic Reference Coordinate System		Present IMU Stable Member Coordinate System	
	\underline{S}'_A	\underline{S}'_B	\underline{S}_A	\underline{S}_B
0	LM Y-axis stored in MFCS	LM Z-axis stored in MFCS	Present LM Y-axis	Present LM Z-axis
1	Landing Site stored in MFCS	LM Z-axis stored in MFCS	Gravity Vector Determination Routine	Present LM Z-axis
2	<u>One or more of the following:</u> <ol style="list-style-type: none"> 1. LGC star catalog 2. Loaded by astronaut 3. Ephemeris (i.e., SUN, EARTH) 		AOT Sighting	AOT Sighting
3	Landing Site stored in MFCS	Same as technique 2 above	Gravity Vector Determination Routine	AOT Sighting

previously determined gravity vector and the unitized sum of the two 1/2-unit gravity vectors just determined. Until P57 is performed for the first time, the LGC assumes that the lunar gravity vector is parallel to the LM X-axis if the Landing Confirmation Program (P68) has been completed. If P68 has not been completed, the VERB 06 NOUN 04 display is meaningless on the first pass through the program. If a remeasure of the lunar gravity vector is desired, the crew must key in VERB 32 ENTR (recycle). If a completion of alignment is desired, the crew must key in PRO. This will complete the alignment as in technique 0 starting with the unit LOS vectors definition. (See Table 7.3.3-II.)

Upon completion of pulsing the gyros through the desired angles to align the IMU, a check is made to determine whether or not the alignment technique is 0. If it is not 0, the INITIAL ALIGN flag is reset and the angle between the actual and indicated alignment vectors is computed and displayed to the crew via a flashing VERB 06 NOUN 05 display in the Sighting Data Display Routine (R54). (See Figure 7.3.3-2.) If the angle is within acceptable limits, the crew keys PRO. P57 will compute the desired gyro torquing angles and display them in a flashing VERB 06 NOUN 93. If these angles are less than 5 degrees, the alignment will be continued as in technique 0 except that the LM attitude will be computed and stored in moon-fixed coordinates. If the angle determined in R54 is out of limits, the crew can key in recycle (VERB 32 ENTR) and start the final alignment procedure.

7.3.3.4.3 Technique 2.—Whenever a complete alignment or realignment is to be performed on the lunar surface using sightings on two celestial bodies, technique 2 must be used. When this technique is used, it is not necessary for either the REFSMMAT flag or the ATTITUDE flag to be set; the initial alignment (technique 0) is bypassed and the Lunar Surface Sighting Mark Routine (R59) is called immediately. If either flag is set, however, technique 0 alignment is completed. P57 then calls R59. (See Figure 7.3.3-3.) R59 is used to perform AOT sightings on celestial bodies while the LM is on the lunar surface. When the computer first enters R59, it determines whether or not the REFSMMAT flag is set. If it is not set, the computations are immediately transferred to the AOT Mark Routine (R53) which will be described later. For the present, it is assumed that the REFSMMAT flag is set. Thus, the crew sees a flashing VERB 01 NOUN 70 display indicating the AOT detent position and the star code. (See Table 7.3.3-I.) The crew can then key in the star code for the celestial body on which it desired to sight. When the proper information is displayed to the crew, it can key in PRO. If the crew has selected a star for its sightings, the computer will calculate, in navigation base coordinates, the star LOS from the star data and the optical axis for the presently defined AOT position code.

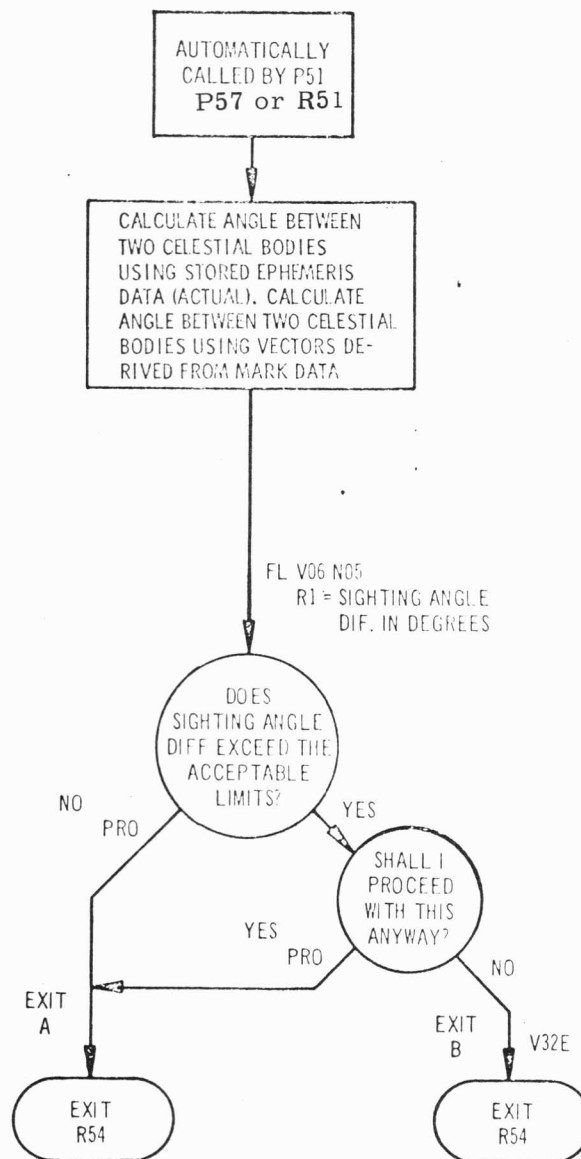


Figure 7.3.3-2. Sighting Data Display Routine (R54)

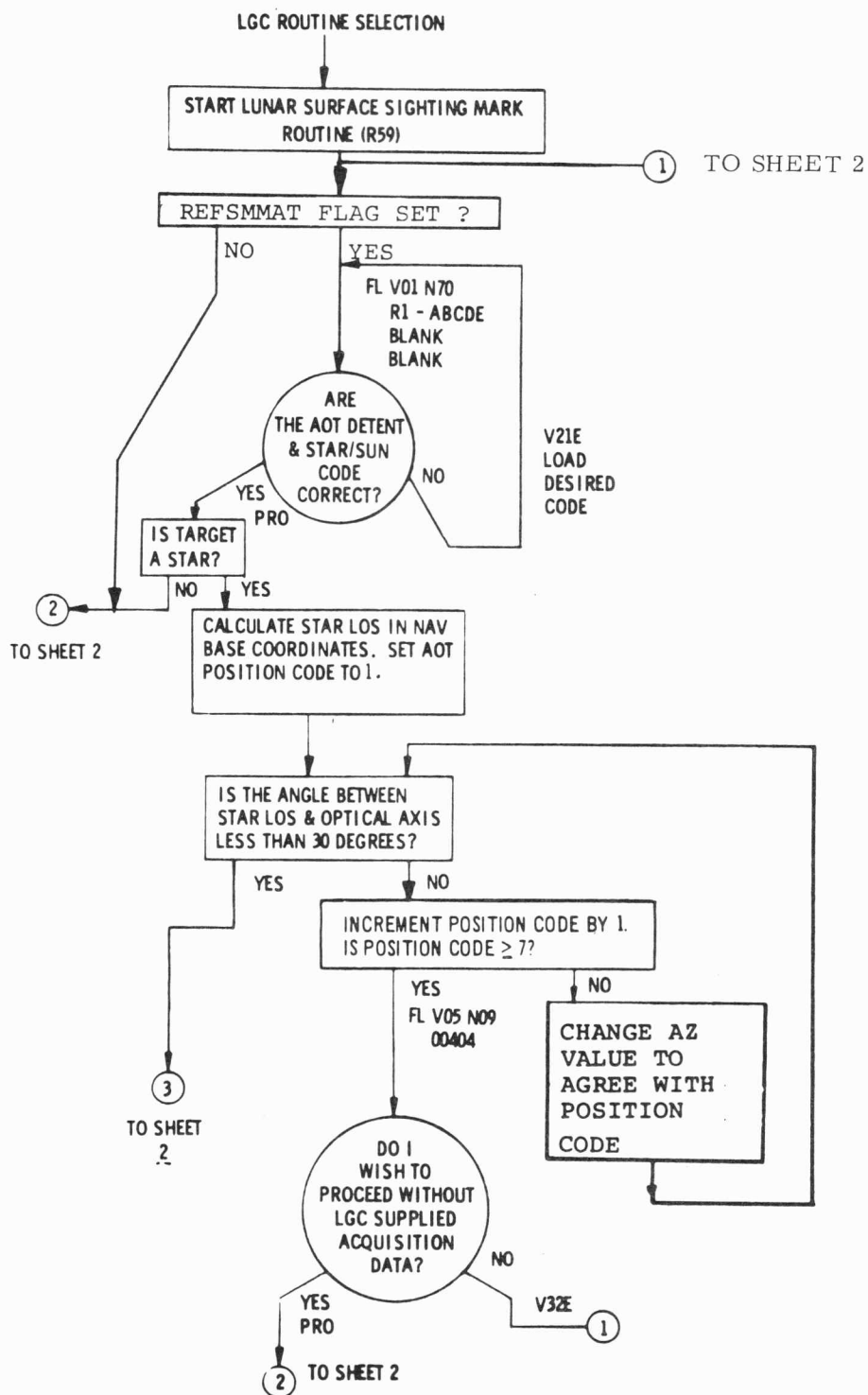


Figure 7.3.3-3. Lunar Surface Sighting Mark Routine (R59) (Sheet 1 of 2)

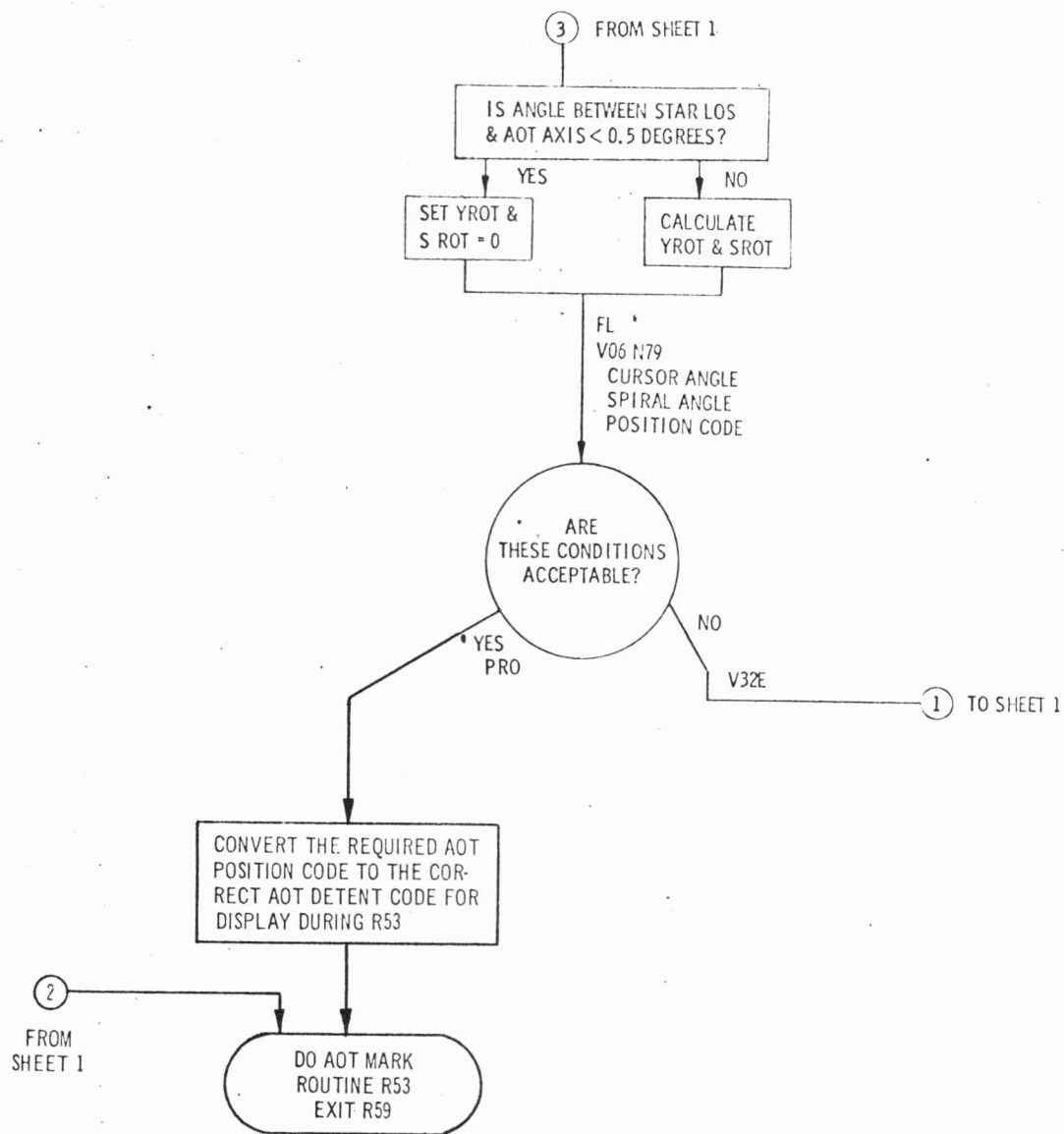


Figure 7.3.3-3. Lunar Surface Sighting Mark Routine (R59) (Sheet 2 of 2)

If the angle between the star LOS and the optical axis is greater than 30 degrees, the position code will be incremented by 1 each time it is checked until the angle is less than 30 degrees. If the AOT position code is incremented through the six AOT positions and the angle between the star LOS and the optical axis is still greater than 30 degrees, a flashing VERB 05 NOUN 09 display will indicate an alarm code 00404 (see paragraph 7.3.3.5), allowing the crew to select another star and repeat the process, or to proceed to R53 without LGC supplied data.

If the angle between the star LOS and optical axis is less than 30 degrees, the cursor and spiral angles are calculated and displayed along with the position code via a flashing VERB 06 NOUN 79. (See Table 7.3.3-I.) The AOT position code is converted to the correct AOT detent code and R53 is called.

The AOT Mark Routine, R53, (see Figure 7.3.3-4) will process the sighting marks on the celestial bodies. While the LM is on the lunar surface, only the AOT may be used for sighting on celestial bodies. Upon initial entry into R53, several checks are made to determine if it is possible to use the routine. (See paragraph 7.3.3.5, alarm codes 20105, 31211, and 31207.) The first display the crew will see in this routine is a flashing VERB 01 NOUN 71 indicating the AOT detent code and star code. (See Table 7.3.3-I.)

If the codes are not those determined previously in R59, the crew may key in VERB 21 ENTR, load the desired codes, and PRO. The next display the crew will see is flashing VERB 54 NOUN 71 requesting a please perform mark X or mark Y reticle line/star intersection. While the LM is on the lunar surface, marks are taken singly by pushing either the MARK X or the MARK Y pushbutton. This is usually accomplished between the measurement and the recording of the angle at the point where the cursor and the star are aligned, and the angle where the spiral and the star are aligned. (See Figure 7.3.3-5.)

By depressing either the MARK X or MARK Y pushbutton, the VERB 06 NOUN 79 display in the Markrupt Routine, R57 (see Figure 7.3.3-6), comes up allowing the crew to load the angles just recorded into registers R1 and R2 by keying in VERB 24 ENTR and then loading the angles. Up to five marks may be taken on a particular celestial body by keying in VERB 32 ENTR after each cursor and spiral angle load. If more than five marks are taken, the PROG alarm light will come on. (See paragraph 7.3.3.5, alarm code 00107.) The LGC will average all the LOS to define a final LOS on a particular celestial body.

After each mark, the crew has the option to terminate marking by keying PRO; continue marking on the same celestial body (with the restriction noted above) by

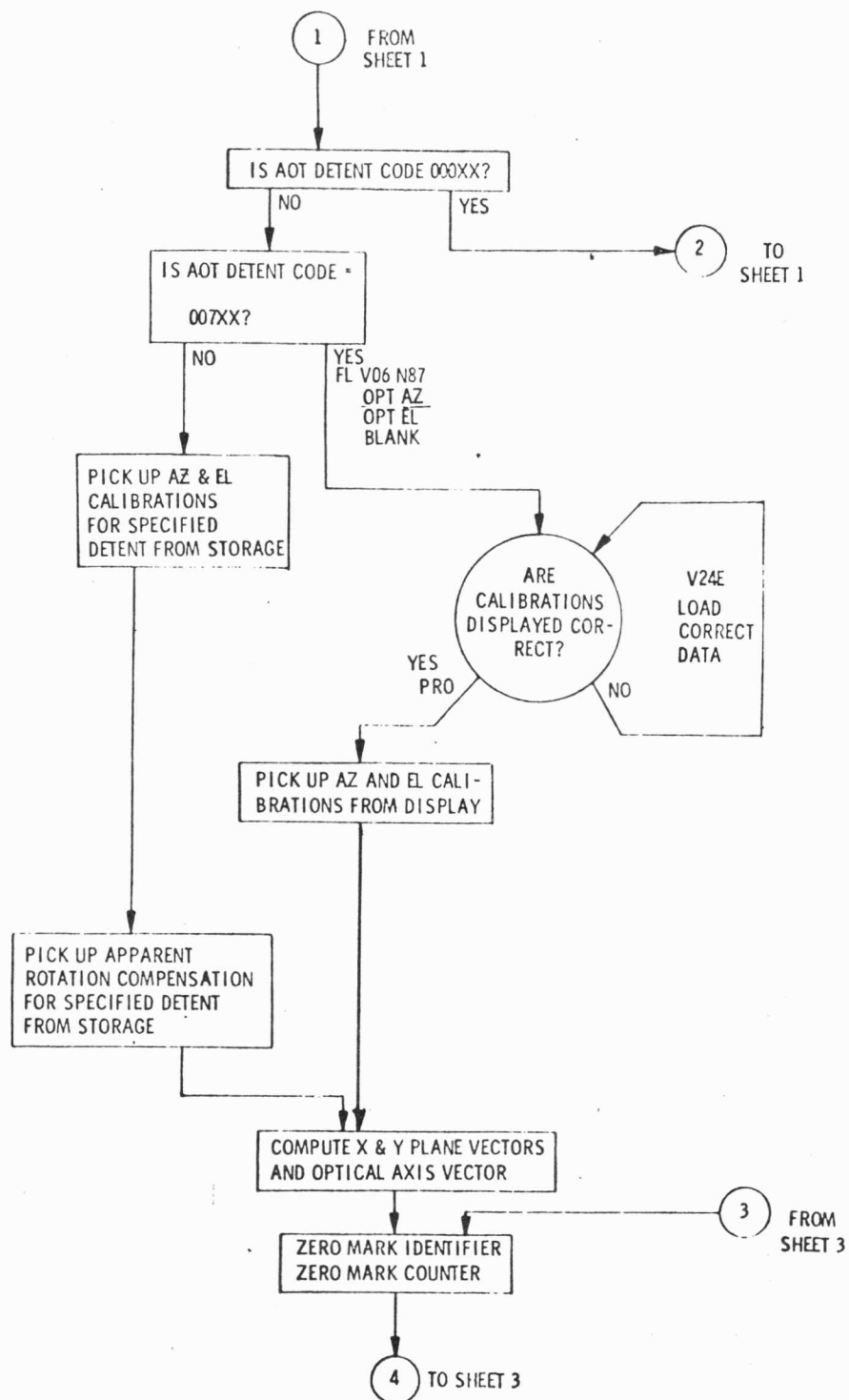


Figure 7.3.3-4. Sighting Mark Routine (R53) (Sheet 2 of 3)

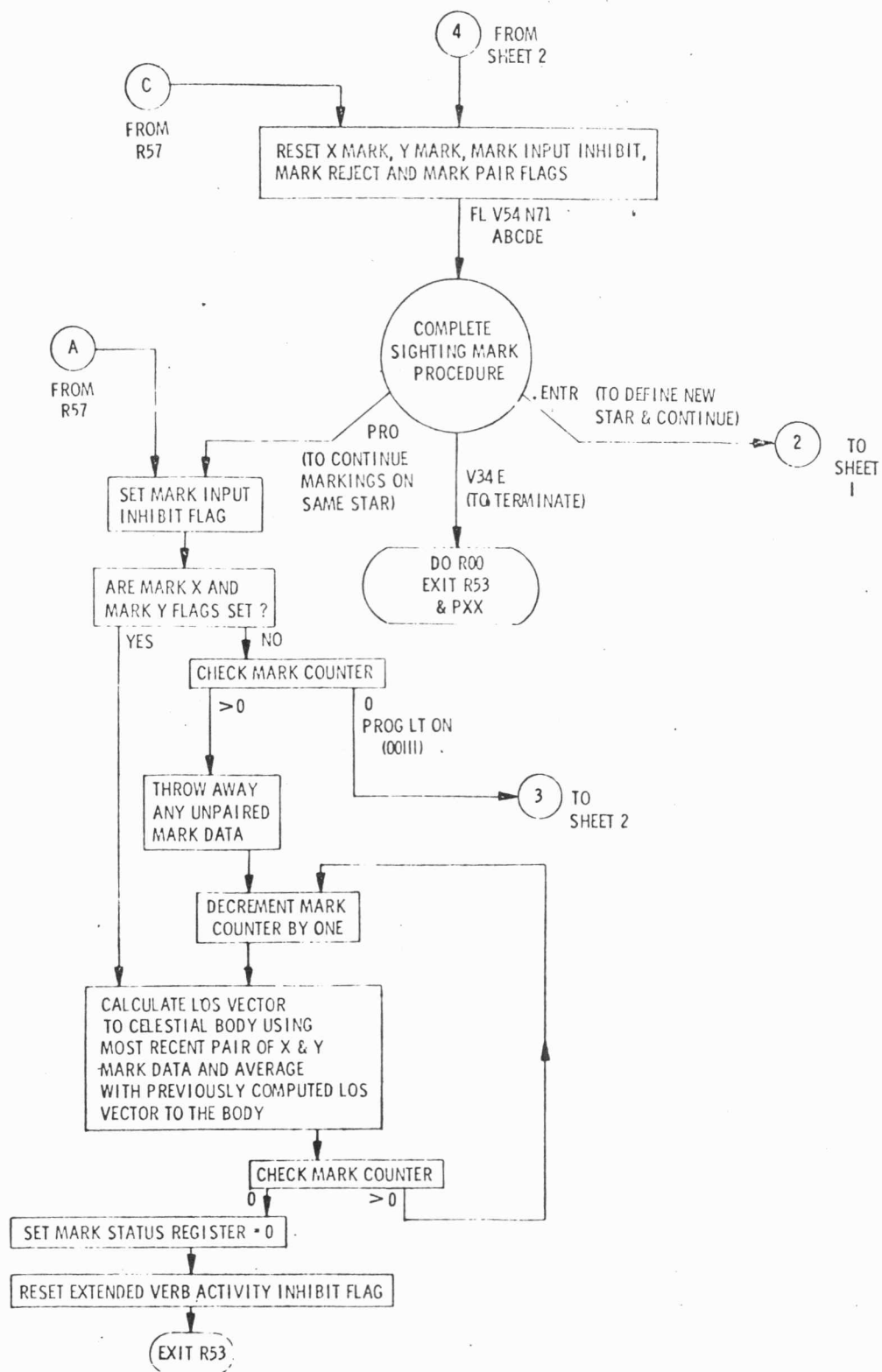


Figure 7.3.3-4. Sighting Mark Routine (R53) (Sheet 3 of 3)

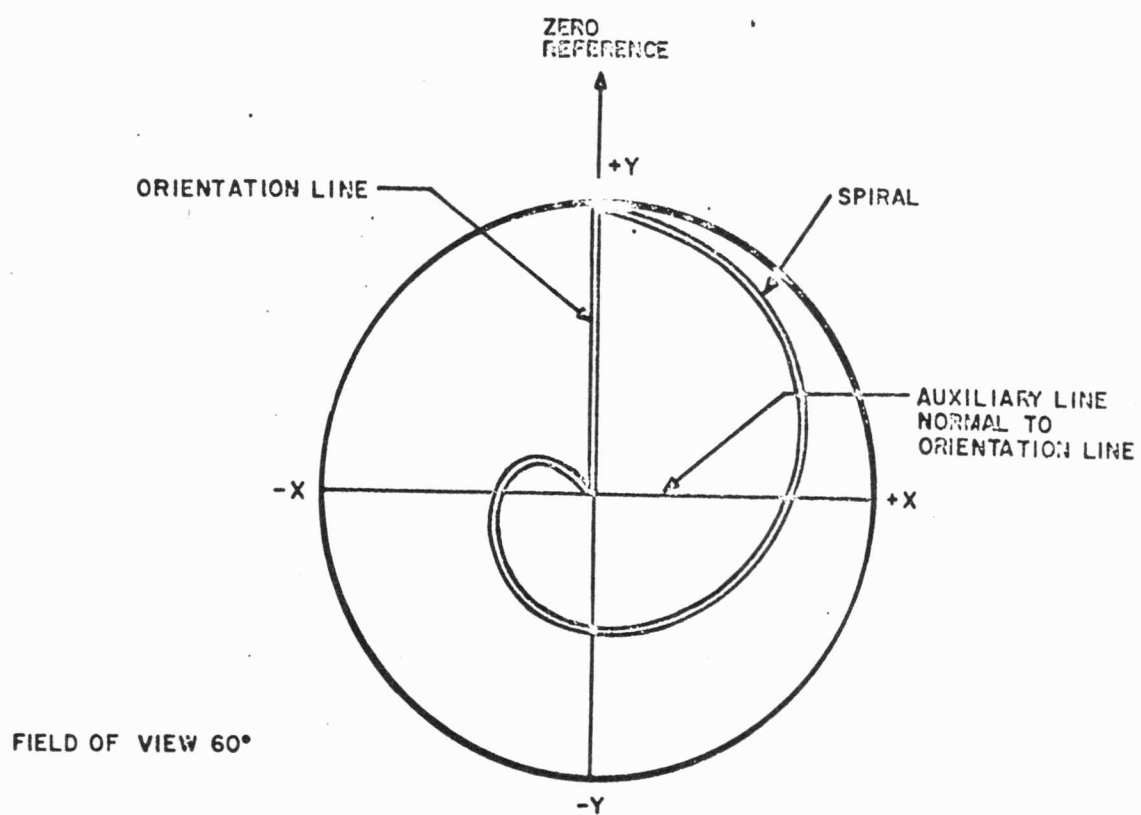


Figure 7.3.3-5. Alignment Optical Telescope Reticle Pattern

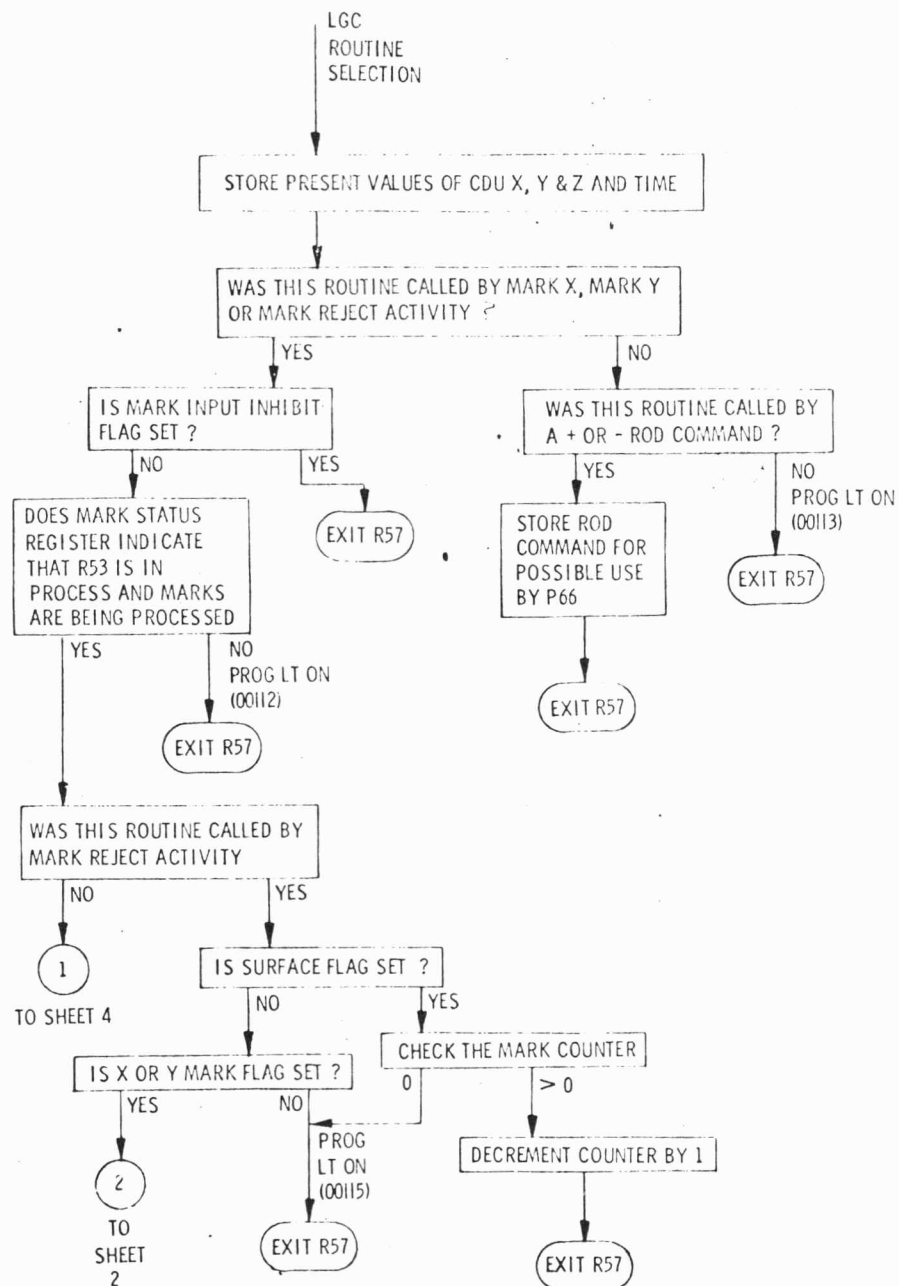


Figure 7.3.3-6. Markrupt Routine (R57) (Sheet 1 of 4)

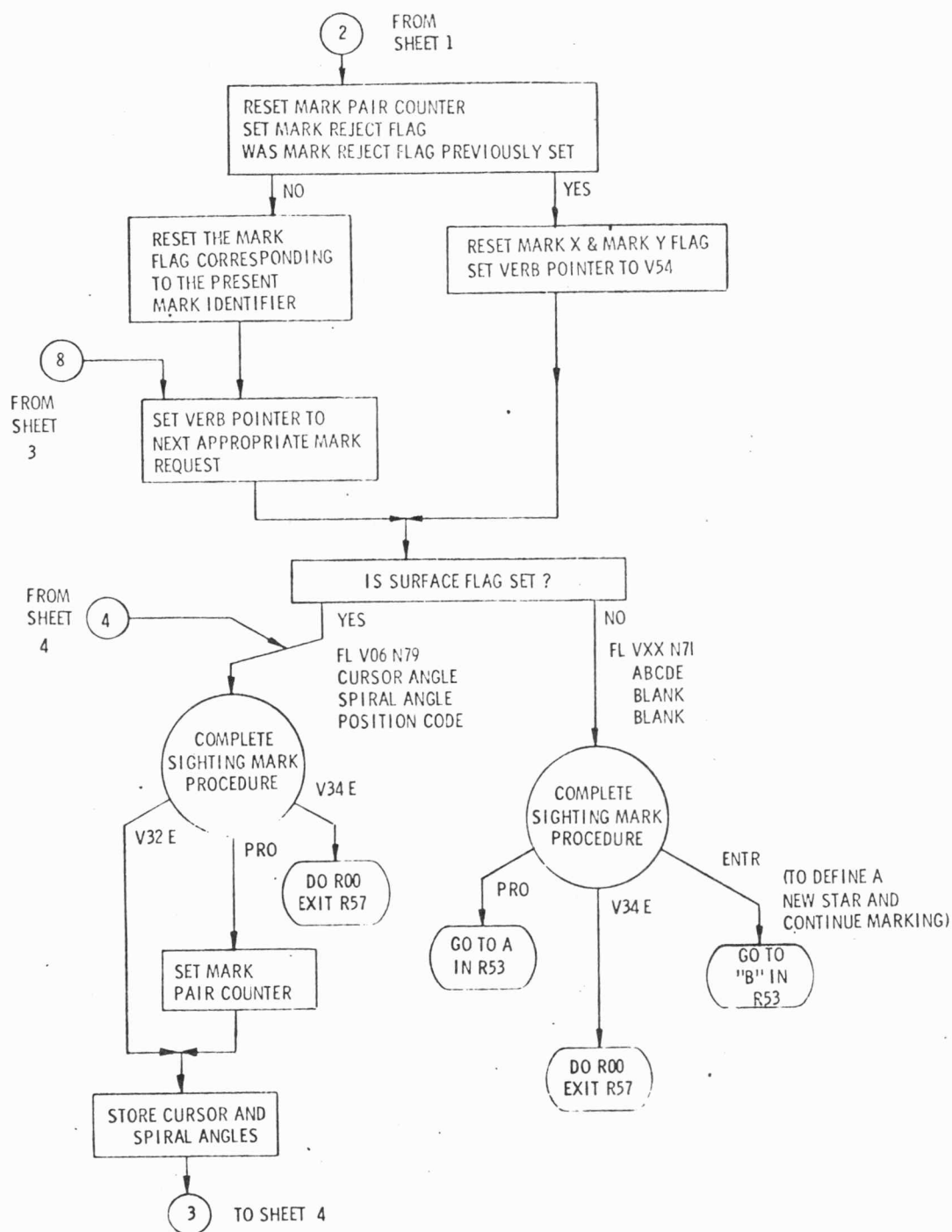


Figure 7.3.3-6. Markrupt Routine (R57) (Sheet 2 of 4)

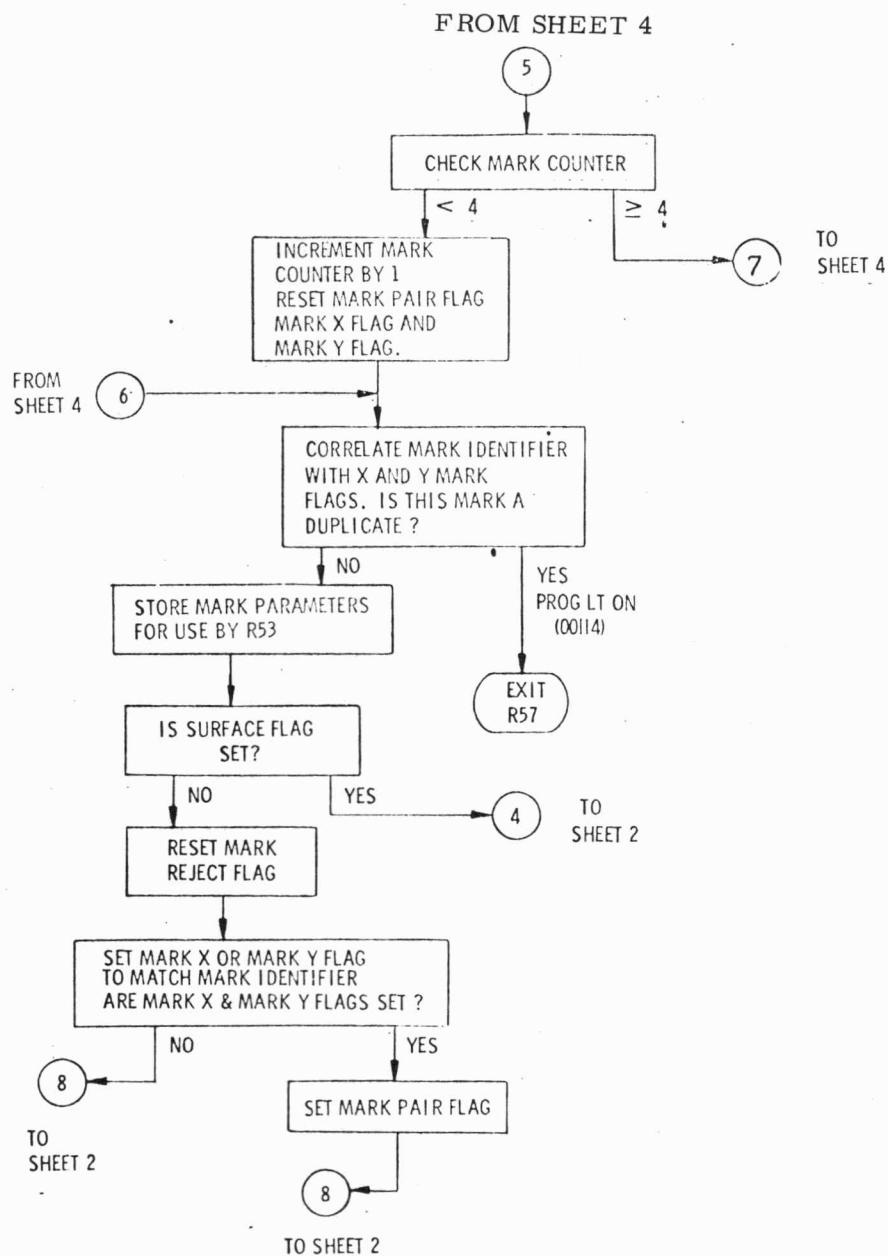


Figure 7.3.3-6. Markrupt Routine (R57) (Sheet 3 of 4)

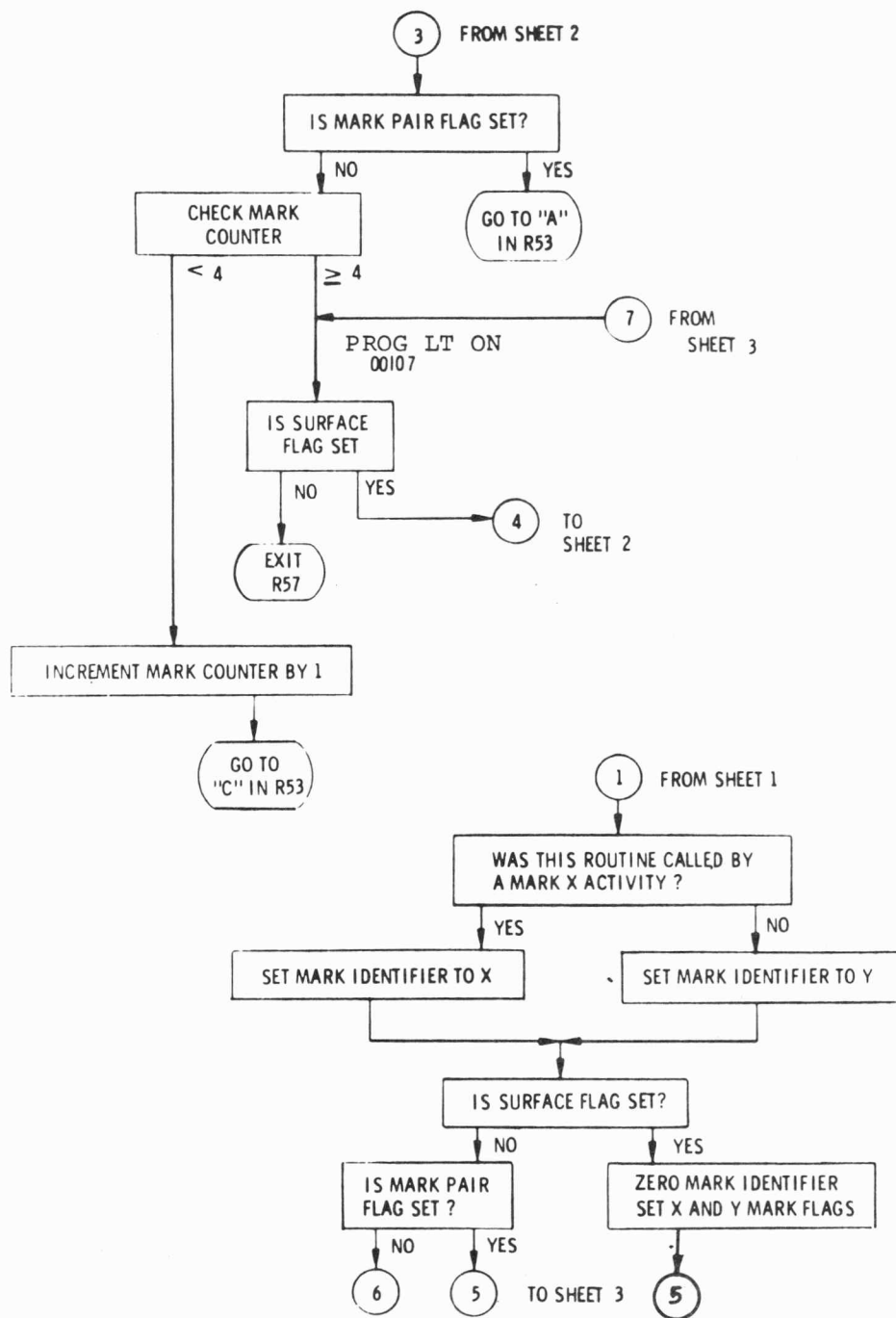


Figure 7.3.3-6. Markrupt Routine (R57) (Sheet 4 of 4)

keying in VERB 32 ENTR (recycle); discard all data on the present celestial body and select a new one by keying in ENTR on the VERB 54 NOUN 71 display, defining the new body, and starting marking; or terminate the entire alignment by keying in VERB 34 ENTR (terminate).

This marking procedure must be performed on two celestial bodies. Their LOS vectors must then be computed with respect to the present stable member to desired IMU coordinates. Once these LOS vectors, together with others obtained from the LGC star catalog or loaded by the crew, or computed from ephemeris data using the Celestial Body Definition Routine, R58, (see Table 7.3.3-I and Figure 7.3.3-7), have been determined, the remaining steps of the alignment process are the same as technique 0.

7.3.3.4.4 Technique 3. — This technique is selected when the complete IMU alignment is to be made by determining the lunar gravity vector, as in technique 1, and sighting one celestial body, as in technique 2.

When using any of these techniques, a request to perform a fine align (VERB 50 NOUN 25 code 00014) is accomplished by keying a PRO from this display. When the crew has keyed in PRO from the VERB 50 NOUN 25 display, the initial align flag has been reset (except in technique 0). The IMU alignment vectors are obtained for the technique being used to align the IMU, as described above, and a realignment is accomplished.

7.3.3.5 Program Alarms

In addition to the anticipated outputs, the program displays a program alarm light and stores an alarm code for display at the crew's discretion. The program will display an alarm (VERB 05 NOUN 09) under the following conditions:

- a. Alarm 00210 is displayed if the IMU is not operating when P57 is first entered.
- b. Alarms 00211 and 00217 are displayed, if at the end of a coarse alignment the gimbals are not within 2 degrees of the desired values.
- c. Alarm 00701 is displayed if neither the present REFSMMAT nor a stored LM attitude is available.
- d. Alarm 31211 is displayed when there is an illegal interrupt by an extended verb.
- e. Alarm 00404 is displayed if in technique 2, two stars are not available in any detent position of the AOT.

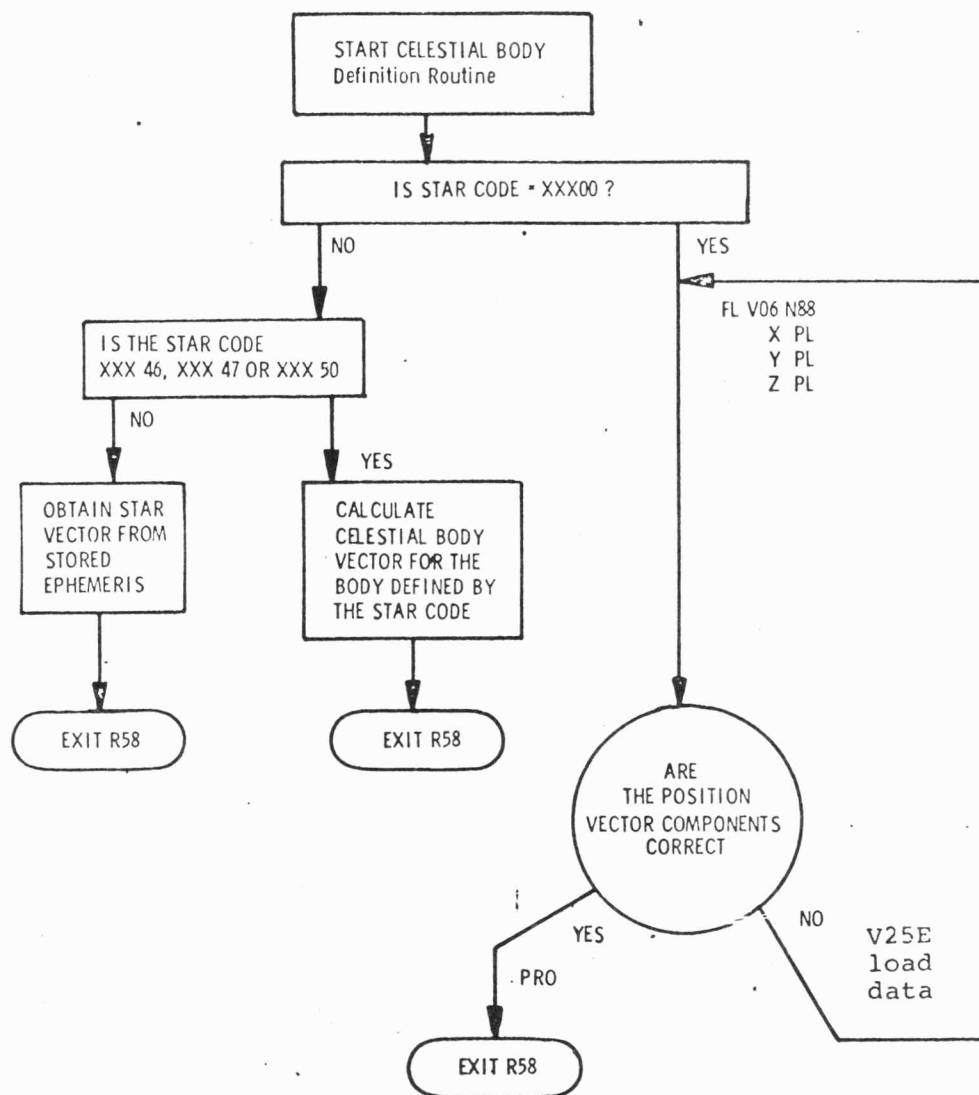


Figure 7.3.3-7. Celestial Body Definition Routine (R58)

- f. Alarm 20105 is displayed if, when the crew wants to start processing marks, the mark register indicates that the AOT mark system is in use.
- g. Alarm 31207 is displayed if there are no VAC areas available for the computation and processing of the marks.
- h. Alarm 00111 is displayed on PROCEED from the NOUN 71 display if there is not enough data (Mark counter = 0) to compute a star vector.
- i. Alarm 00107 is displayed if more than five marks have been taken on a single celestial body.

The ISS must be on and at either a known or an unknown orientation in order to align the IMU using P57. If the ISS is not on, alarm code 00210 will alert the crew to press the IMU OPERATE circuit breaker and allow 15 minutes for warm-up before re-initializing P57.

When using alignment techniques 1 or 3 and prior to the start of coarse alignment of the ISS, the outer gimbal, inner gimbal, and middle gimbal are set to +42 degrees, -42 degrees and +35.25 degrees, respectively. Upon completion of the coarse align, if the gimbals are not within 2 degrees of these values, alarm codes 00211 and 00217 will alert the crew and a realignment may be accomplished. Following the NOUN 04 display, a VERB 34 ENTR may be keyed in to terminate the current calculation, and P57 entered again by keying in VERB 37 ENTR 57 ENTR and selecting technique 1 or 3 again. Or VERB 32 ENTR (recycle) may be keyed in to recycle to the point where the expected gimbal angles are set. When using this method, the gravity vector that has been previously calculated and stored is then compared to the recalculation rather than to the originally defined gravity vector.

In NOUN 70 when a star code is selected, the AOT is set to 1 and the angle between the star LOS and the optical axis is calculated. If the difference is greater than 30 degrees, the AOT position is incremented by 1. If upon searching all 7 positions the difference is still greater than 30 degrees, a flashing VERB 05 NOUN 09 is displayed automatically with alarm code 00404. The crew may key in VERB 32 ENTR and recycle to a point from which to select a different star and determine the angle between that star and the AOT optical axis, or may key in PRO and start taking marks via the AOT Mark Routine (R53).

When the alignment telescope marking system is in use and the crew desires to start processing additional marks, the PROG alarm light may go on, indicating that it is impossible at this time to process additional marks. Alarm code 20105 will be displayed by keying in VERB 05 NOUN 09. If this alarm does occur, the program

will automatically go to R00 and the whole marking process will have to be re-initiated via the calling program. The alarm code displayed could also be 31207 indicating that no VAC areas were available for storing parameters for computations of mark information. If this alarm occurs, the computer does an automatic restart, releasing all the VAC areas, and recycles to the beginning of R53.

Register 1 of the NOUN 71 display shows the AOT detent and star codes. Marks on the indicated star are made singly by depressing either the MARK X pushbutton, or the MARK Y pushbutton. If for any reason the mark counter equals 0 when PRO is keyed on NOUN 71, the PROG alarm light will come on. Upon keying VERB 05 NOUN 09, an alarm code 00111 will come up. This situation may be remedied by taking a mark, keying in the NOUN 79 data, and then keying PRO. After each mark, the crew may either terminate marking by keying in PRO; continue marking on the same celestial body (if less than five marks are already stored in the LGC); discard all data, select a new celestial body and continue marking by keying in ENTR; or terminate the whole alignment by keying in VERB 34 ENTR (terminate).

The mark counter in the LGC keeps track of the number of marks taken on a particular celestial body. If, while the LM is on the lunar surface, the number of marks registered by the counter exceeds five, the PROG alarm light will come on. The crew, by keying in VERB 05 NOUN 09, may determine that the alarm code is 00107, indicating that more than five marks have been taken on that particular celestial body.

7.3.3.6 Restart

P57 is restart protected. Should a restart occur, the program will return to one of several predetermined points, depending on where in the program the restart occurred. The program will then continue to completion.

Internal Distribution

Group 23A	<u>S. MacDougall</u>	<u>IL 7-205</u>	10
	T. Brand	G. Levine	
	P. Brennan	E. Muller	
	P. Chin	C. Pu	
	J. Higgins	M. Reber	
	P. Kachmar	W. Robertson	
Group 23B	<u>J. Kaloostian</u>	<u>IL7-221L</u>	12
	A. Bancroft	B. Ireland	
	C. Beals	S. Jennings	
	N. Brodeur	J. Laird	
	T. Crocker	N. Neville	
	J. Goode	W. Ostanek	
	R. Haslam	R. Whittredge	
Group 23B	<u>D. Lutkevich</u>	<u>IL7-228</u>	38
	C. Babicki	H. Kana	
	G. Beck	J. Klawnsnik	
	W. Danforth	H. Maher	
	R. Daniel	H. Nayar	
	F. Decain	J. Reed (20)	
	R. Entes	D. Reinke	
	J. Flaherty	J. B. Smith	
	J. Glendenning	F. Williams	
	J. Good	P. Wolff	
	H. Hubbard		
Group 23B	<u>C. Taylor</u>	<u>IL7-221L</u>	16
	N. Barnert	M. Hamilton	
	B. Bramley	D. Hsiung	
	A. Carter	E. Hughes	
	M. Cramer	D. Lollar	
	T. Crowley	S. Rosenberg	
	V. Demery	P. Rye	
	D. Densmore	N. Smith	
	S. Eliassen		
	A. Engel		
Group 23H	<u>B. Lynn</u>	<u>IL7-234A</u>	4
	S. Deutsch	G. Kossuth	
	S. Goldberger	J. O'Connor	
Group 23C	<u>M. Erickson</u>	<u>IL11-102</u>	8
	R. Bairnsfather	A. Penchuk	
	D. Fraser	R. Schlundt	
	G. Kalan	R. Stengel	
	D. Keene	J. Turnbull	

Group 23D	<u>F. McGann</u> G. Dimock J. Dunbar I. Johnson R. Kiburz R. Metzinger E. Olsson	<u>IL7-332</u> R. Schulte A. Sewall S. Schroeder S. Smith F. Walsh W. Woolsey	12
Group 23D	<u>S. Prangley</u> J. Nevins	<u>IL7-209</u>	1
Group 23P	<u>C. Mitaris</u> S. Copps	<u>IL7-213</u> R. Larson	2
Group 23P	<u>A. Rubin</u> D. Hoag	<u>IL7-252</u> L. Larson	2
Group 23P	<u>E. Johnson</u> R. Ragan	<u>IL7-248</u> W. Stameris	2
Group 23S	<u>P. Amsler</u> M. Adams P. Felleman H. McOuat	<u>IL7-240</u> R. Strunce R. Werner R. White	6
Group 23T	<u>D. Farrell</u> W. Day G. Edmonds E. Grace K. Kido J. Lawrence R. Lones	<u>IL7-140</u> V. Megna J. Reedy N. Sears G Silver J. St. Armand	11
Group 23N	<u>G. Grover</u> E. Blanchard L. B. Johnson	<u>IL11-202</u> G. Ogletree T. Parr	4
Group 33	<u>J. Hargrove</u> L. Drane K. Glick	<u>IL7-111</u> P. Mimno M. Johnson	4
Group 23P	<u>J. Sutherland</u> K. Greene	<u>IL7-266</u> G. Stubbs	2
APOLLO Library			2
MIT/IL Library			2

External Distribution List

NASA MSC/FSB
Building 30
Kennedy Space Center, Florida 32815
Attn: G. Sabionski, FS5

(50)