MASSACHUSETTS INSTITUTE OF TECHNOLOGY

APOLLO

GUIDANCE, NAVIGATION AND CONTROL

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R-577

GUIDANCE SYSTEM OPERATIONS PLAN FOR MANNED CM EARTH ORBITAL AND LUNAR MISSIONS USING PROGRAM COLOSSUS 2 (COMANCHE REV. 44, 45)

SECTION 5 GUIDANCE EQUATIONS (Rev. 5)

MARCH 1969

MIT INSTRUMENTATION LABORATORY
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R-577

GUIDANCE SYSTEM OPERATIONS PLAN FOR MANNED CM EARTH ORBITAL AND LUNAR MISSIONS USING PROGRAM COLOSSUS

SECTION 5 GUIDANCE EQUATIONS

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REVISION INDEX COVER SHEET
GUIDANCE SYSTEM OPERATIONS PLAN

GSOP #R-577 Title: For Manned CM Earth Orbital and Missions Using Program Colossus II (Comanche Revision 44, 45)

Section #5 Title: Guidance Equations (Revision 5)

This revision of GSOP R-577 describes the guidance equations utilized in Program Colossus II and is issued as a completely new document. Revision 4 should be retained as the control document for Colossus I and IA.

PCR and PCN changes are indicated by denoting the applicable number at the bottom of the page and indicating the location of the change by a black line ▌ on the side of the page. Editorial corrections (not covered by PCR or PCN) are denoted by black dots : .

Below is a list of the PCR's and PCN's incorporated in this GSOP. In addition, for convenience, the PCR's and PCN's included in previous issues are listed.

PCR - (PCN*)		TITLE
		<u>Incorporated in Revision 1</u>
3		Attitude Error Display During First 10 Seconds of Launch (P-11)
60.1		30° - 76° Star Selection Capability in Auto Optics
63		Delete TLI Program
64		Add v, h and $\dot{h}$ Display to P-47
80.3	*	State Vector Synchronization
81		AUGE-KUGEL Coefficient Change
87	*	Initiation of Average-G Routine
88.1		Navigation Filter Variances Shifted to Erasable Memory
94	*	Entry Guidance Logic Modifications
108	*	P-37 Description Modification
109	*	Cross Product Steering Constant c Clarification
130		Backward Integration at Lunar Sphere of Influence
146.3	*	Emergency Termination of Integration Function
149	*	Low Altitude, High Inclination Correction in P-37
155		Lift-Vector-Up Roll Attitude When Drag Less Than 0.05 g's
160	*	Return-to-Earth Targeting Constants
166	*	Correct Setting of ORBW Flag (Partial)
168	*	IMU Error Variance Correction
171.1	*	Targeting Interface with P-40 and P-41
173.1	*	RMS Position and Velocity Error Display
176	*	N-Second Lambert Cycle Updates
183.2	*	Section 5 Control Data Update
193	*	Low Thrust Detection Modification
199	*	Section 5 Update Based on MIT and MSC Reviews
200	*	P-61 Title Change to Entry Preparation Program
404	*	Lunar Landmark Selection Routine Equation Modification

PCR - (PCN*)		Incorporated in Revision 2
176	*	N-Second Lambert Updates (Reworked)
198	*	GSOP Update Section 4
220		Colossus Entry Logic Modifications
226		Change Priority Displays from 5 seconds to 2 seconds
439.1		Downgrade Preferred Orientation Flag
442	*	P-37 V-Gamma Polynomial Coefficients
462	*	Lambert Error in P-17
465	*	Resetting of VHFRFLAG and STIKFLAG
468		Change R-32 to Program P-76
485	*	Increase Entry Steering DAP Damping
491	*	Longer wait periods in R-22
501		Low Thrust Threshold in Erasable
505	*	SPS Engine Mechanical Bias
506	*	Correction to Time of Flight Calculation in P-61

PCR - (PCN*)		Incorporated in Revision 3
166	*	Correct Setting of ORBW Flag (Complete)
231		Redefine P-41 Preferred Orientation
507.1		Termination of Integration
509		Eliminate P11 Interlock in R30
510	*	Account for 7.96 sec. of Ullage
517	*	No 90° Alarm for Trunnion Angle

PCR - (PCN*)		Incorporated in Revision 3
519	*	Calculation of ϕ in R34
521		Change C Steering Constant in P37
522		Put COAS Variance in Erasable
524		Provide MAX Display for Perigee and Apogee in P30, P31, R30
525		Increase Altitude above Earth for Disturbing Acceleration
526		Variance for Integration Errors in Navigation
528		Display Change in P67
529		Inhibit Lateral Switch in P65
570	*	GSOP Change in R22
573.1	*	Definition of A_X and A_Y in GSOP
590	*	GSOP Error in Time-to-Go
597	*	Advanced Ground Track Error
621	*	Correct SPS Engine Data
626	*	Engine Flag in P37
628	*	COLOSSUS GSOP Section 5 Update

PCR - (PCN*)		Incorporated in Revision 4
250		MDOT in Erasable (Colossus IA)
544	*	Correction to Fixed Memory Constant
602		Permanent LM State Vector Update with SURFFLAG Set (Colossus IA)
611		Use 6-Dimensional Matrix for V67 Computations (Colossus IA)

PCR - (PCN*)		Incorporated in Revision 5
251		Spacecraft Backup for Saturn V Platform Failure
254.1		Modification of CDH Time Computation Logic
255		Option on Out-of-plane Display Computations
256		Eliminate R35 and All Fixed Memory Lunar Landmarks

PCR - (PCN*)		Incorporated in Revision 5
261		Range Override of P37 Entry Range Calculations
572		IMU Pulse Torquing
576.1	*	Removal of Backward Updating Constraint on State Vector
638		KA Limit
655		Range Limit in Augekugel Program
659.1	*	Suppression of X Moduloing by Kepler
661	*	Test for State Vector Origin Change at the End of Integration
663		Δv Magnitude Display for P37
664	*	P23 Calculation of Secondary Body to CSM Vector
665		R31, R34 Improvement
668	*	Test for State Vector Origin Change Based on Total Position Vector Only
681	*	Concentric Rendezvous Maneuver Targeting, CSI/CDH
682	*	Add Code "00" to P23
684	*	P37 Alarm when Altitude < 400,000 ft
686		Nominal Orientation for P52/P54 Using Precision Integration
690		Trans-Earth Coast Slow Down Capability for P37
691		P37 Δv_{LV} Display
692	*	Time-Theta and Time-Radius Alarm Abort
694	*	Abort Coasting Integration when in Infinite Acceleration Overflow Loop
724	*	Correct REFSMMAT Gravity Computation in P11
729		Certain SPS Impulse Data in Erasable
730		H, V, γ Display with P21
733		Increase Entry Speed Limit in P37
734	*	Change SPS Impulse Fixed Data

SECTION 5

GUIDANCE EQUATIONS

5.1 INTRODUCTION

5.1.1 GENERAL COMMENTS

The purpose of this section is to present the Guidance and Navigation Computation Routines associated with the CSM Apollo Lunar Landing Mission. These Routines are utilized by the Programs outlined in Section 4 where astronaut and other subsystem interface and operational requirements are described. The guidance and navigation equations and procedures presented in Section 5 are primarily concerned with mission type programs representing the current CSM GNCS Computer (CMC) capability. A restricted number of CMC service type program operations which involve computation requirements are also included.

The CSM GNCS Computer (CMC) guidance and navigation equations for the lunar landing mission are presented in the following six categories:

Section 5.2	Coasting Flight Navigation Routines
Section 5.3	Powered Flight Navigation and Guidance Routines
Section 5.4	Targeting Routines
Section 5.5	Basic Subroutines
Section 5.6	General Service Routines
Section 5.7	Entry Guidance

Guidance equation parameters required for program initialization and operation are listed in Section 5.8. These selected parameters are stored in the CMC erasable memory. General constants used in the equations of this volume are presented in Section 5.9.

A complete table of contents for Section 5 is presented in the following Section 5.1.2.1. A cross-reference between the CMC programs and routines of Section 4 that are described in Section 5 is listed in Section 5.1.2.2. In the following Section 5 table of contents and text, missing section numbers correspond to COLOSSUS programs that have been deleted from the previous Section 5 GSOP's by MSC direction resulting from the CMC Fixed Memory Storage Review Meeting of August 28, 1967, and subsequently approved Program Change Requests (PCR) by the Software Change Control Board (SCB).

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The Guidance System Operations Plan is published as seven separate volumes (sections) as listed below:

Section 1	Pre-Launch
Section 2	Data Links
Section 3	Digital Auto-Pilots
Section 4	Operational Modes
Section 5	Guidance Equations
Section 6	Control Data
Section 7	Error Analyses

This volume constitutes a control document to govern the structure of the CSM Lunar Landing Mission, using COLOSSUS, including GNCS interfaces with the flight crew and Mission Control Center.

Revisions to this plan which reflect changes in the above control items require NASA approval.

5.1.2 TABLE OF CONTENTS

5.1.2.1 Section 5 Table of Contents

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5.1.2.2 Sections 4 and 5 Cross Reference

PROGRAM NUMBER	TITLE	PRINCIPAL SECTION 5 SUBSECTION NO.	PAGE
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P-11	Earth Orbit Injection (EOI) Monitor Program	5.3.5	5.3-47
P-17	CSM TPI Search Program	5.4.2.4	5.4-27
P-20	Rendezvous Navigation Program	5.2.5	5.2-63
P-21	Ground Track Determination Program	5.6.5	5.6-30
P-22	Orbital Navigation Program	5.2.4	5.2-41
P-23	Cislunar Navigation Program	5.2.6	5.2-84
P-30	External ΔV Maneuver Guidance	5.3.3.3.1	5.3-17
P-31	Lambert Aim Point Maneuver Guidance	5.3.3.3.2	5.3-21
P-32	Coelliptic Sequence Initiation (CSI) Program	5.4.2.1.1	5.4-4
P-33	Constant Differential Altitude (CDH) Program	5.4.2.1.2	5.4-17
P-34	Transfer Phase Initiation (TPI) Guidance	5.4.2.2	5.4-18
P-35	Transfer Phase Midcourse (TPM) Guidance	5.4.2.3	5.4-24
P-37	Return to Earth Maneuver Guidance	5.4.3	5.4-43
P-38	Stable Orbit Rendezvous Guidance	5.4.2.5	5.4-35
P-39	Stable Orbit Rendezvous Midcourse Guidance	5.4.2.5.3	5.4-40

PROGRAM NUMBER	TITLE	PRINCIPAL SECTION 5 SUBSECTION NO.	PAGE
P-40	SPS Thrust Program	5.3.3	5.3-6
P-41	RCS Thrust Program	5.3.3	5.3-6
P-47	Thrust Monitor Program	5.3.4	5.3-47
P-51	IMU Orientation Determination	5.6.2.1	5.6-2
P-52	IMU Realignment Program	5.6.2.2	5.6-6
P-53	Backup IMU Orientation Determination	5.6.2.3	5.6-12
P-54	Backup IMU Realignment Prog.	5.6.2.4	5.6-12
P-61	Entry Preparation Program	5.7	5.7-1
P-62	CM/SM Separation and Pre-Entry Maneuver	5.7	5.7-1
P-63	Entry Initialization	5.7	5.7-1
P-64	Post 0.05 G Entry Mode	5.7	5.7-1
P-65	Up Control Entry Mode	5.7	5.7-1
P-66	Ballistic Entry Mode	5.7	5.7-1
P-67	Final Entry Mode	5.7	5.7-1
P-72	LM (CSI) Targeting	5.4.2.1.1	5.4-4
P-73	LM (CDH) Targeting	5.4.2.1.2	5.4-17
P-74	LM Transfer Phase Initiation (TPI) Targeting	5.4.2.2	5.4-18
P-75	LM Transfer Phase Midcourse (TPM) Targeting	5.4.2.3	5.4-24
P-76	Target ΔV Program	5.6.14	5.6-84
P-77	LM TPI Search Program	5.4.2.4	5.4-27
P-78	LM Stable Orbit Rendezvous	5.4.2.5	5.4-35
P-79	LM Stable Orbit Rendezvous Midcourse Targeting	5.4.2.5.3	5.4-40

ROUTINES	TITLE	SECTION 5 SUBSECTION NO.	PAGE
R-05	S-Band Antenna	5.6.6	5.6-31
R-21	Rendezvous Tracking Sighting Mark	5.2.5.1	5.2-63
R-22	Rendezvous Tracking Data Processing	5.2.5.2	5.2-70
R-23	Backup Rendezvous Tracking Sighting Mark	5.2.5.1	5.2-63
R-30	Orbit Parameter Display	5.6.10	5.6-51
R-31	Rendezvous Parameter Display Routine Number 1	5.6.7.1	5.6-34
R-34	Rendezvous Parameter Display Routine Number 2	5.6.7.2	5.6-35
R-36	Rendezvous Out-of-Plane Display	5.6.7.4	5.6-37
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R-41	State Vector Integration (MID to AVE) Routine	5.3.3.3.4	5.3-32
R-50	Coarse Align	5.6.2.2	5.6-6
R-52	Automatic Optics Positioning	5.6.8	5.6-39
R-53	Sighting Mark	5.6.2.1 5.6.2.2	5.6-2 5.6-6
R-54	Sighting Data Display	5.6.2	5.6-2
R-55	Gyro Torquing	5.6.2.2	5.6-6
R-56	Alternate LOS Sighting Mark	5.6.2.3 & 4	5.6-12
R-61	Tracking Attitude	5.2.5.1	5.2-63
R-63	Rendezvous Final Attitude	5.6.7.3	5.6-37

5.1.3 GENERAL PROGRAM UTILIZATION

The following outline is a brief summary of the major CMC programs and callable routines that would be used in the principal phases of a lunar landing mission. This outline reflects the CMC capability for the nominal and abort cases of such a mission.

I Earth Orbit Injection (EOI) Phase

A) Nominal

P - 11 Earth Orbit Insertion (EOI) Monitor Program

B) Abort to Entry

P - 61 Entry Preparation Program

P - 62 CM / SM Separation Maneuver Program

P - 63 Entry Initialization Program

P - 64 Post 0.05 G Entry Program

P - 67 Final Entry Phase Program

II. Earth Orbit Phase

A) Nominal

P-27 CMC Update Program (State vector update).

R-30 Orbit Parameter Display Routine

B) Aborts to Entry

1. RTCC Targeted Abort

P-27 CMC Update Program (De-orbit targeting).

P-30 External ΔV Maneuver Program (De-orbit)

(or)

P-31 Lambert Aim Point Maneuver Program (De-orbit)

P-40, P-41 — SPS or RCS Thrust Program

P-61, P-62, P-63, P-64, P-67 — Entry Programs

II Earth Orbit Phase (cont)

B. Aborts to Entry

2. CMC Targeted Abort

P - 22	Lunar Orbit Navigation Program (Earth Mode)
P - 21	Ground Track Program
P - 37	Return to Earth Program (Targeting and Pre-Thrust)
P - 40, P - 41	SPS or RCS Thrust Program
P - 61, P - 62, P - 63, P - 64, P - 67	Entry Programs

C) Service Programs (Nominal and Abort Cases)

P - 52	IMU Realignment Program
P - 00	CMC Idling Program
R - 30	Orbit Parameter Display Routine

III Trans-Lunar Injection (TLI) Phase

A) Nominal

P - 47 Thrust Monitor Program (TLI Maneuver Monitoring)

B) Aborts to Earth Entry

1. RTCC Targeted Abort

P - 27 CMC Update Program (Return to earth maneuver targeting).

P - 30 External ΔV Pre-Thrust Program

P - 31 Lambert Aim Point Pre-Thrust Program

P - 40, P - 41 SPS or RCS Thrust Program

P - 61 to P - 67 Entry Programs

III Trans-Lunar Injection (TLI) Phase (cont)

B) Aborts to Entry

2. CMC Targeted Abort

P - 23 Cislunar Navigation Program

P - 37 Return to Earth Program (Targeting and Pre-Thrust)

P - 40 }
P - 41 } SPS or RCS Thrust Programs

P - 61 }
to } Entry Programs
P - 67 }

C) Service Programs Used in Abort Cases

P - 51 IMU Orientation Determination

P - 52 IMU Realignment Program

P - 06 GNCS Power Down

P - 00 CMC Idling

IV Trans-Lunar Phase

A) Nominal (Midcourse Correction Maneuvers)

P - 27 CMC Update Program (State vector update and cislunar MCC maneuver targeting).

P - 30 External ΔV Pre-Thrust Program
or
P - 31 Lambert Aim Point Pre-Thrust Program

P - 40 }
P - 41 } SPS or RCS Thrust Program

P - 47 Thrust Monitor Program (Manual Transposition and Docking Maneuver)

B) Aborts to Earth Entry

1. RTCC Targeted Abort

P - 27 CMC Update Program (Return to earth maneuver targeting).

P - 30 External ΔV Pre-Thrust Program
or
P - 31 Lambert Aim Point Pre-Thrust Program

P - 40 }
P - 41 } SPS or RCS Thrust Program

IV Trans-Lunar Phase (cont)

B) Aborts to Earth Entry

2. CMC Targeted Abort (Limited Capability)

P - 23	Cislunar Navigation Program
P - 37	Return to Earth Program Targeting and Pre-Thrust (Capability limited to outside lunar sphere of influence)
P - 40 / P - 41	SPS or RCS Thrust Programs
P - 61 to P - 67	Entry Programs

C) Service Programs for Nominal and Abort Cases

P - 06	GNCS Power Down
P - 51	IMU Orientation Determination
P - 52	IMU Realignment Program
P - 00	CMC Idling Program
R - 05	S-Band Antenna Routine

V Lunar Orbit Insertion (LOI) Phase

A) Nominal

P - 27 CMC Update Program (State vector update and LOI maneuver targeting).

P - 30 External V Maneuver Program (Second LOI Maneuver)

P - 31 Lambert Aim Point Pre-Thrust Program (First LOI Maneuver)

P - 40 SPS Thrust Program

B) Aborts to Return to Earth Trajectory

1. RTCC Targeted Abort

P - 27 CMC Update Program (Return to earth maneuver targeting).

P - 30 External ΔV Pre-Thrust Program (To establish safe lunar orbit if required)

P - 31 Lambert Aim Point Pre-Thrust Program (TEI)

P - 40 SPS Thrust Program

V Lunar Orbit Insertion (LOI) Phase (cont)

B) Aborts to Return to Earth Trajectory

2. CMC Semi-Controlled Abort (Limited Capability)

P - 22	Lunar Orbit Navigation Program
P - 21	Ground Track Program
P - 27	CMC Update Program (TEI targeting).
P - 31	Lambert Aim Point Pre-Thrust Program (TEI)
P - 40	SPS Thrust Program

C) Service Programs for Nominal and Abort Cases

P - 52	IMU Realignment Program
R - 05	S-Band Antenna Routine

VI Lunar Orbit Phase Prior to LM Descent Orbit Injection

A) Nominal

P - 22 Lunar Orbit Navigation Program

P - 21 Ground Track Program

P - 27 CMC Update Program (Lunar Landing timing and targeting parameters)

R - 33 CMC/LGC Clock Synchronization Routine

P - 76 Target ΔV Program (LM Separation)
or
P - 47 Thrust Monitor Program (CSM Separation)

P - 20 Rendezvous Navigation Program (Tracking Mode only for LM RR Check-Out)

B) Aborts to Return to Earth Trajectory

1. RTCC Targeted Abort

P - 27 CMC Update Program (TEI targeting and State vector update).

P - 31 Lambert Aim Point Pre-Thrust Program (TEI)

P - 40 SPS Thrust Program

VI Lunar Orbit Phase Prior to LM Descent Orbit Injection (cont)

B) Aborts to Return to Earth Trajectory

2. CMC Semi-Controlled Abort (Limited Capability)

P - 22	Lunar Orbit Navigation Program
P - 21	Ground Track Program
P - 27	CMC Update Program (TEI targeting)
P - 31	Lambert Aim Point Pre-Thrust Program (TEI)
P - 40	SPS Thrust Program
P - 47	Thrust Monitor Program (TEI by DPS Case)

C) Service Programs for Nominal and Abort Cases

P - 06	GNCS Power Down
P - 51	IMU Orientation Determination
P - 52	IMU Realignment Program
P - 00	CMC Idling Program
R - 05	S-Band Antenna Routine
R - 30	Orbit Parameter Display Routine

VII LM Descent Orbit Injection (DOI), Descent Coast and Landing Phases

A) Nominal

P - 20 Rendezvous Navigation Program (Tracking attitude and monitoring only)

B) Aborts to Rendezvous Condition

1. LM Active Vehicle

P - 20 Rendezvous Navigation Program

P - 76 Target ΔV Program

P - 74 LM TPI Targeting Program (Monitoring or commands via voice link)

P - 75 LM TPM Targeting Program (Rendezvous MCC monitoring or commands via voice link)

P - 77 TPI Search Program (LM mode)

P - 78 LM Stable Orbit Rendezvous Targeting Program

P - 79 LM Stable Orbit Rendezvous Midcourse Targeting Program

P - 21 Ground Track Program

VII LM Descent Orbit Injection (DOI), Descent Coast and Landing Phases (cont)

B) Aborts to Rendezvous Condition

2. CSM Active Retrieval

P - 27	CMC Update Program (State vector update and phasing maneuver targeting if required)
P - 20	Rendezvous Navigation Program
P - 30	External ΔV Pre-Thrust Program
P - 17	CSM TPI Search Program
P - 21	Ground Track Program
P - 34	TPI Pre-Thrust Program
P - 35	TPM Pre-Thrust Program
P - 38	Stable Orbit Rendezvous Program
P - 39	Stable Orbit Rendezvous Midcourse Program
P - 40 P - 41	SPS or RCS Thrust Programs
P - 47	Thrust Monitor Program (Manual terminal rendezvous maneuver)

C) Service Programs

P - 52	IMU Realignment Program
R - 31	Rendezvous Parameter Display Routine No. 1
R - 34	Rendezvous Parameter Display Routine No. 2
R - 36	Out of Plane Rendezvous Display Routine
R - 63	Rendezvous Final Attitude Routine
P - 00	CMC Idling
R - 05	S-Band Antenna Routine
R - 30	Orbit Parameter Display Routine

VIII Lunar Stay Phase to LM Ascent Launch

A) Nominal

P - 22	Lunar Orbit Navigation Program (for landing site surveillance and CMC update if desired)
P - 21	Ground Track Program
P - 27	CMC Update Program (LM launch time update and Lunar Orbit Plane Change LOPC, targeting).
P - 31	Lambert Aim Point Pre-Thrust Program (LOPC)
(or)	
P - 30	External ΔV Pre-Thrust Program (LOPC)
P - 40	SPS Thrust Program
P - 20	Rendezvous Navigation Program (Tracking attitude and monitoring only)

B) Service Programs

P - 51	IMU Orientation Determination
P - 52	IMU Realignment Program
P - 00	CMC Idling Program
R - 05	S-Band Antenna Routine
R - 30	Orbit Parameter Display Routine

IX LM Ascent and Rendezvous Phase

A) Nominal

P - 20	Rendezvous Navigation Program (Preferred Tracking Attitude during LM launch)	
P - 27	CMC Update Program	LM injection state vector
(or)		
P - 76	Target ΔV Program	
P - 20	Rendezvous Navigation Program (LM state vector updating)	
R - 32	Target ΔV Routine	
P - 74	LM TPI Targeting Program (Monitoring)	
P - 75	LM TPM Targeting Program (Monitoring)	
P - 78, P - 79	LM Stable Orbit Rendezvous Programs (Monitoring)	
P - 21	Ground Track Program	

B) Aborts to Rendezvous Condition

1. LM Active Vehicle

P - 27	CMC Update Program (State vector updates)
P - 20	Rendezvous Navigation Program
P - 76	Target ΔV Program
P - 74	LM TPI Targeting Program (Monitoring)
P - 75	LM TPM Targeting Program (Monitoring)
P - 78, P - 79	LM Stable Orbit Rendezvous Programs (Monitoring)
P - 21	Ground Track Program
P - 77	LM TPI Search Program

IX LM Ascent and Rendezvous Phase (cont)

B) Aborts to Rendezvous Conditions

2. CSM Active Retrieval

P - 27	CMC Update Program (State vector updates and phasing maneuver targeting if required)
P - 20	Rendezvous Navigation Program
P - 30	External ΔV Pre-Thrust Program (Targeted from RTCC or LGC)
P - 17	CSM TPI Search Program
P - 38	Stable Orbit Rendezvous Program
P - 39	Stable Orbit Rendezvous Midcourse Program
P - 21	Ground Track Program
P - 34	TPI Pre-Thrust Program
P - 35	TPM Pre-Thrust Program
P - 40 P - 41	SPS or RCS Thrust Programs
P - 47	Thrust Monitor Program (Manual terminal rendezvous maneuver)

C) Service Programs for Nominal and Abort Cases

P - 52	IMU Realignment Program
R - 05	S-Band Antenna Routine
R - 31	Rendezvous Parameter Display Routine No. 1
R - 34	Rendezvous Parameter Display Routine No. 2
R - 36	Out of Plane Rendezvous Display Routine
R - 63	Rendezvous Final Attitude Routine
R - 30	Orbit Parameter Display Routine
P - 00	CMC Idling Program

X Lunar Orbit Phase Prior to TEI

A) Nominal

P - 27 CMC Update Program (State vector update)

(or)

P - 22 Lunar Orbit Navigation Program

P - 21 Ground Track Program

P - 52 IMU Realignment Program

P - 00 CMC Idling Program

P - 47 Thrust Monitor (Manual CSM-LM Separation Maneuver)

B) Aborts Prior to Nominal TEI

P - 27 CMC Update Program (State vector update)

XI Trans-Earth Injection (TEI) Phase

A) Nominal

P - 27 CMC Update Program (TEI target parameters for P-31)

P - 31 Lambert Aim Point Pre-Thrust Program

P - 40 SPS Thrust Program

B) Aborts to Earth Return Trajectory

Same as nominal case

No CMC targeting capability

XII Trans-Earth Phase Midcourse Correction Maneuvers

A) Nominal

P - 27	CMC Update Program (Cislunar midcourse correction maneuver targeting)
P - 31 or P - 30	Lambert Aim Point Pre-Thrust Program / External ΔV Pre-Thrust Program
P - 40, P - 41	SPS or RCS Thrust Program

B) Aborts to Maintain Earth Return Trajectory (CMC Limited Capability)

P - 23	Cislunar Navigation Program
P - 37	Return to Earth Program (Outside lunar sphere of influence only)
P - 40, P - 41	SPS or RCS Thrust Programs

C) Service Programs for Nominal and Abort Cases

P - 06	GNCS Power Down
P - 51	IMU Orientation Determination
P - 52	IMU Realignment Program
R - 05	S-Band Antenna Routine
P - 00	CMC Idling Program

XIII Entry Phase

A) Nominal

P - 61 Entry Preparation Program

P - 62 CM / SM Separation Maneuver

P - 63 Entry Initialization

P - 64 Post 0.05 G Entry Phase

P - 65 Entry Up Control Phase

P - 66 Entry Ballistic Phase

P - 67 Final Entry Phase

5.1.4 COORDINATE SYSTEMS

There are six major coordinate systems used in the navigation and guidance programs. These six coordinate systems are defined individually in the following descriptions and referenced to control specifications of Section 5.9.2 where applicable. Any other coordinate system used in any particular CMC program is defined in the individual section describing that program.

5.1.4.1 Basic Reference Coordinate System

The Basic Reference Coordinate System is an orthogonal inertial coordinate system whose origin is located at either the moon or the earth center of mass. The orientation of this coordinate system is defined by the line of intersection of the mean earth equatorial plane and the mean orbit of the earth (the ecliptic) at the beginning of the Besselian year which starts January 0.525, 1969. The X-axis ($\underline{u}_{XI}$) is along this intersection with the positive sense in the direction of the ascending node of the ecliptic on the equator (the equinox), the Z-axis ($\underline{u}_{ZI}$) is along the mean earth north pole, and the Y-axis ($\underline{u}_{YI}$) completes the right-handed triad. The Basic Reference Coordinate System is presented in Ref. 1 of Section 5.9.2 as Standard Coordinate System 4, Geocentric Inertial in Fig. A-4.

This coordinate system is shifted from earth-centered to moon-centered when the estimated vehicle position from the moon first falls below a specified value r_{SPH}, and is likewise shifted from moon-centered to earth-centered when the estimated vehicle position from the moon first exceeds r_{SPH}. This procedure is described in Section 5.2.2.6 and Fig. 2.2-3. All navigation stars and lunar-solar ephemerides are referenced to this coordinate system. All vehicle state vectors are referenced to this system.

5.1.4.2 IMU Stable Member or Platform Coordinate System

The orthogonal inertial coordinate system defined by the GNCS inertial measurement unit (IMU) is dependent upon the current IMU alignment. There are many possible alignments during a mission, but the primary IMU alignment orientations described in Section 5.6.3.3 are summarized below and designated by the subscript SM:

1. Preferred Alignment

$$\underline{u}_{XSM} = \text{UNIT}(\underline{x}_B)$$
$$\underline{u}_{YSM} = \text{UNIT}(\underline{u}_{XSM} \times \underline{r}) \qquad (1.4.1)$$
$$\underline{u}_{ZSM} = \underline{u}_{XSM} \times \underline{u}_{YSM}$$

where:

$\left.\begin{matrix}\underline{u}_{XSM}\\ \underline{u}_{YSM}\\ \underline{u}_{ZSM}\end{matrix}\right\}$ IMU stable member coordinate unit vectors referenced to the Basic Reference Coordinate System

$\underline{x}_B$ = vehicle or body X-axis at the preferred vehicle attitude for ignition

$\underline{r}$ = position vector at ignition

2. Nominal Alignment (Local Vertical)

$$\underline{u}_{XSM} = (\underline{u}_{YSM} \times \underline{u}_{ZSM})$$
$$\underline{u}_{YSM} = \text{UNIT}(\underline{v} \times \underline{r}) \qquad (1.4.2)$$
$$\underline{u}_{ZSM} = \text{UNIT}(-\underline{r})$$

where $\underline{r}$ and $\underline{v}$ represent the vehicle state vector at the alignment time, t_{align}.

3. Earth Pre-launch Alignment

Prior to earth launch the IMU stable member is aligned to a local vertical axis system where

$\underline{u}_{ZSM}$ = UNIT $(-\underline{r})$ (local vertical)

$\underline{u}_{XSM}$ = UNIT $(\underline{A})$ where $\underline{A}$ is a horizontal vector pointed at the desired launch azimuth angle.

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

4. Lunar Landing Alignment

$$
\begin{aligned}
\underline{u}_{XSM} &= \text{UNIT}\ (\underline{r}_{LS})\ \text{at}\ t_L \\
\underline{u}_{ZSM} &= \text{UNIT}\ \left[(\underline{r}_C \times \underline{v}_C) \times \underline{u}_{XSM}\right] \\
\underline{u}_{YSM} &= \underline{u}_{ZSM} \times \underline{u}_{XSM}
\end{aligned}
\qquad (1.4.3)
$$

where $\underline{r}_{LS}$ is the lunar landing site vector at the predicted landing time, t_L, and $\underline{r}_C$ and $\underline{v}_C$ are the CSM position and velocity vectors, as maintained in the CMC.

5. Lunar Launch Alignment

The same as that defined in Eq. (1.4.3) except that $\underline{r}_{LS}$ is the landing or launch site at the predicted launch time t_L.

The origin of the IMU Stable Member Coordinate System is the center of the IMU stable member.

5.1.4.3 Vehicle or Body Coordinate System

The Vehicle or Body Coordinate System is the orthogonal coordinate system used for the CSM structural body. The origin of this coordinate system is on the longitudinal axis of the CSM, 1000 inches below the mold line of the heat shield main structure ablator interface. The X-axis ($\underline{u}_{XB}$) lies along the longitudinal axis of the vehicle, positive in the nominal SPS thrust direction. The positive Z-axis ($\underline{u}_{ZB}$) is defined by an alignment target (labeled +Z) at the top of the service module and is normal to $\underline{u}_{XB}$. The Y-axis ($\underline{u}_{YB}$) completes the right-handed triad. This coordinate system is defined in Ref. 1 of Section 5.9.2 as the Standard Coordinate System 8c, CSM Structural Body Axes in Fig. A-8c.

5.1.4.4 Earth-Fixed Coordinate System

The Earth-Fixed Coordinate System is an orthogonal rotating coordinate system whose origin is at the center of mass of the earth. This coordinate system is shown in Ref. 1 of Section 5.9.2 as the Standard Coordinate System 1, Geographic Polar in Fig. A-1. The Z-axis of this coordinate system is defined to be along the earth's true rotational or polar axis. The X-axis is defined to be along the intersection of the prime (Greenwich) meridian and the equatorial plane of the earth, and the Y-axis is in the equatorial plane and completes the right-handed triad.

5.1.4.5 Moon-Fixed Coordinate System

The Moon-Fixed Coordinate System is an orthogonal rotating coordinate system whose origin is at the center of mass of the moon. This coordinate system is shown in Ref. 1 of Section 5.9.2 as the Standard Coordinate System 2, Selenographic Polar in Fig. A-2. The Z-axis is defined to be along the true polar or rotation axis of the moon, the X-axis is through the mean center of the apparent disk or along the intersection of the meridian of 0° longitude and the equatorial plane of the moon, and the Y-axis is in the equatorial plane and completes the right-handed triad.

5.1.4.6 Navigation Base Coordinate System

The Navigation Base Coordinate System (subscript NB) is an orthogonal coordinate system whose orientation is essentially parallel to that of the CSM Vehicle Coordinate System. The Y_{NB} axis is defined by the centers of the two upper mounts between GNCS navigation base and the CM structure located at vehicle station points $X_C = 71.185$ and $Z_C = 35.735$ in Ref. 13 of Section 5.9.2. The positive Y_{NB} direction is in the same general direction as the CSM +Y axis. The Z_{NB} axis is defined as a line measured from the center line of the optics (shown in Section A-A of Ref. 1) through an angle of $32^{\circ}\ 31'\ 23.19''$ about the Y_{NB} axis towards the vehicle +Z axis, and located on the Y_{NB} axis half way between the mount points. The positive Z_{NB} axis is in the same general direction as the vehicle +Z axis. The X_{NB} axis is defined as $\underline{Y}_{NB} \times \underline{Z}_{NB}$ to complete the right-handed triad.

5.1.5 GENERAL DEFINITIONS AND CONVENTIONS

In this section the definitions of and the conventions for using a selected number of parameters are given. Although virtually all of the information in this section appears elsewhere in this document, this section provides a summary of facts which are distributed among various other sections.

5.1.5.1 Error Transition Matrix Maintenance

5.1.5.1.1 Definitions

The error transition matrix (W matrix) is defined in Section 5.2.2.4 and is used in processing navigation measurement data. Control of the W matrix is maintained by means of two flags, RENDWFLG (see Section 5.2.5.2.2) and ORBWFLAG (see Sections 5.2.4.5 and 5.2.6.4). If RENDWFLG is equal to one, then the W matrix is valid for processing rendezvous navigation data; while ORBWFLAG being equal to one indicates that the W matrix is valid for processing orbit or cislunar-midcourse navigation data. If both of these flags are equal to zero, then the W matrix is invalid. These two flags are mutually exclusive; that is, they cannot both be equal to one.

5.1.5.1.2 W Matrix Control Flags

The two W matrix control flags are maintained according to the following rules:

1. RENDWFLG and ORBWFLAG are both initially zero.

2. A CSM state vector update from the ground causes both flags to be zeroed.

3. A LM state vector update from the ground causes RENDWFLG to be zeroed.

4. There exists a special DSKY verb by which the astronaut can zero both flags, and a procedure for zeroing either one (See Section 5.6.16).

5. Indication to the CMC by the astronaut that the LM is on the lunar surface causes RENDWFLG to be zeroed.

6. Initialization of the W matrix for rendezvous navigation causes ORBWFLAG to be zeroed and RENDWFLG to be set to one.

7. Initialization of the W matrix for orbit or cislunar-midcourse navigation causes RENDWFLG to be zeroed and ORBWFLAG to be set to one.

With regard to the last two items 6 and 7 above, there exist in erasable memory three sets of initialization parameters for the W matrix: one for rendezvous navigation, one for orbit navigation, and one for midcourse navigation. Each of these sets contains two elements, a position element and a velocity element. At the time each item of navigation data is processed, the appropriate W matrix control flag is tested. If the flag is found to be zero, then the W matrix is initialized consistent with the appropriate erasable parameters, and the flags are set as indicated in items 6 and 7. See Sections 5.2.4.5, 5.2.5.2.2, and 5.2.6.4 for precise details of this initialization procedure.

5.1.5.1.3 W Matrix Extrapolation

Extrapolation of the W matrix is described in Section 5.2.2.4. Required in this extrapolation is the specification of the appropriate vehicle's state vector with which the W matrix is extrapolated. This extrapolation occurs during programs P-00, P-20, P-22, and P-23; and at the conclusion of programs P-40, P-41, and P-47. The conventions under which the extrapolation occurs during each of these programs are as follows:

P-00 :	The W matrix is extrapolated with the CSM (LM) state vector if ORBWFLAG (RENDWFLG) is equal to one. The W matrix is not extrapolated if both flags are equal to zero. (See Section 5.6.12.)
P-20 :	The W matrix is extrapolated with the state vector that is being updated if RENDWFLG is equal to one, and not extrapolated if RENDWFLG is equal to zero. (See Section 5.2.5.2.2.)
P-22, P-23 :	The W matrix is extrapolated with the CSM state vector if ORBWFLAG is equal to 1, and not extrapolated if ORBWFLAG is equal to zero. (See Sections 5.2.4.5 and 5.2.6.4.)
P-40, P-41, P-47 :	The result of the maneuver will be a final state vector at the end-of-maneuver time t_F. The CSM state vector that existed before the maneuver program will still exist; and, cotemporal with it, there will also be the LM state vector and the W matrix. The following steps are performed after the Average-G Routine (Sec. 5.3.2) is terminated:

1. If either W matrix control flag is equal to one, the old CSM state vector and the W matrix are extrapolated to time t_F.

2. The CSM state vector is initialized to the end-of-maneuver state vector.

3. The LM state vector is extrapolated to time t_F.

If a computation overflow occurs during any of the above W matrix extrapolations, a program alarm will result, both W matrix control flags will be zeroed, and the extrapolation of the state vector will continue without the W matrix.

5.1.5.2 Altitude Parameter Convention

In the following programs and routines the display parameter of the vehicle altitude or trajectory pericenter or apocenter altitude is measured with respect to the earth launch pad radius magnitude, r_{LP}, in earth orbit cases, or the lunar landing site radius magnitude, r_{LS}, in lunar orbit cases. The earth launch pad radius parameter, r_{LP}, is stored in fixed memory, and the lunar landing site radius, r_{LS}, is the magnitude of the landing site vector, $\underline{r}_{LS}$, available in erasable memory.

P-11	Earth Orbit Injection Monitor Program	Section 5.3.5
P-17 & 77	CSM and LM TPI Search Programs	Section 5.4.4.4
P-21	Ground Track Determination Program	Section 5.6.5
P-30	External ΔV Maneuver Guidance	Section 5.3.3.3.1
P-31	Lambert Aim Point Maneuver Guidance	Section 5.3.3.3.2
P-34 & 74	TPI Pre-Thrust Programs	Section 5.4.4.2
R-30	Orbit Parameter Display Routine	Section 5.6.15

The differential altitude, Δh, of programs P-17 and P-77 is measured with respect to the CSM and LM orbits at a specified position vector.

The earth and lunar landmark coordinates required in programs P-22 (Orbit Navigation Program) and P-23 (Cislunar Navigation Program) involve an altitude parameter referenced to the Fischer ellipsoid for earth landmarks, and the mean lunar radius, r_M, for lunar landmarks.

The 400,000 foot and EMS altitude parameters used in the Entry program P-61 (Section 5.6.10) are referenced to the Fischer ellipsoid. The entry altitude of 400,000 feet used in the Return to Earth Guidance Program P-37 is likewise referenced to the Fischer ellipsoid.

5.1.5.3 Lunar Landing Site Definition

The lunar landing site is maintained in the CMC as a vector, $\underline{r}_{LS}$, in the Moon Fixed Coordinate System of Section 5.1.4.5. This landing site vector is stored in erasable memory prior to earth launch and can be changed in lunar orbit either by the Orbital Navigation Program P-22 (Section 5.2.4) or by the RTCC uplink program P-27. The final landing site vector existing in the CSM prior to CSM-LM separation in lunar orbit is used to initialize the LM Guidance Computer (LGC) for the LM descent and landing phases. This landing site initialization vector is referred to as the most recently designated landing site in Section 4.

5.1.5.5 Time Definitions

Mission time t (or ground elapsed time GET) is maintained by the Guidance Computer clock and is measured relative to lift-off time.

The time t_M is that time used to interrogate the planetary orientation and ephemeris routines and is defined in Section 5.5.4.

The time t_0 is that time interval between the beginning of the ephemeris year (July 1 of the year in question) and the time at which mission time is zeroed. Time t_0 is utilized in computing t_M. Shortly before launch, the mission time t is zeroed and t_0 is established utilizing the ground check-out system ACE and the uplink (Verb 55) and down link. Within 0.5 second of the time the computer receives the lift-off discrete, mission time is again zeroed and t_0 is incremented by the elapsed time since the last zeroing of mission time (see program P-11 - Section 5.3.5).