PROJECT APOLLO; COMMAND AND LUNAR MODULES FLIGHT SOFTWARE VERIFICATION AND VALIDATION - A CASE HISTORY

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CONTENTS

Contract Definition & Scope

- Prime contract (NASA-JSC) with MIT/IL to conduct a Navigation and Guidance System Development Program which would "provide a general on-board guidance and navigation capability for the various earth-orbital and cislunar missions". Required for the LUNAR LANDING
- Design responsibility covered both hardware and software
- Contract negotiated separate from development of the Apollo space craft
- Deliverables: Flight software and prototype PGNCS system
- Initial contract let in 1961

MAJOR MISSION TASKS

OBJECTIVES

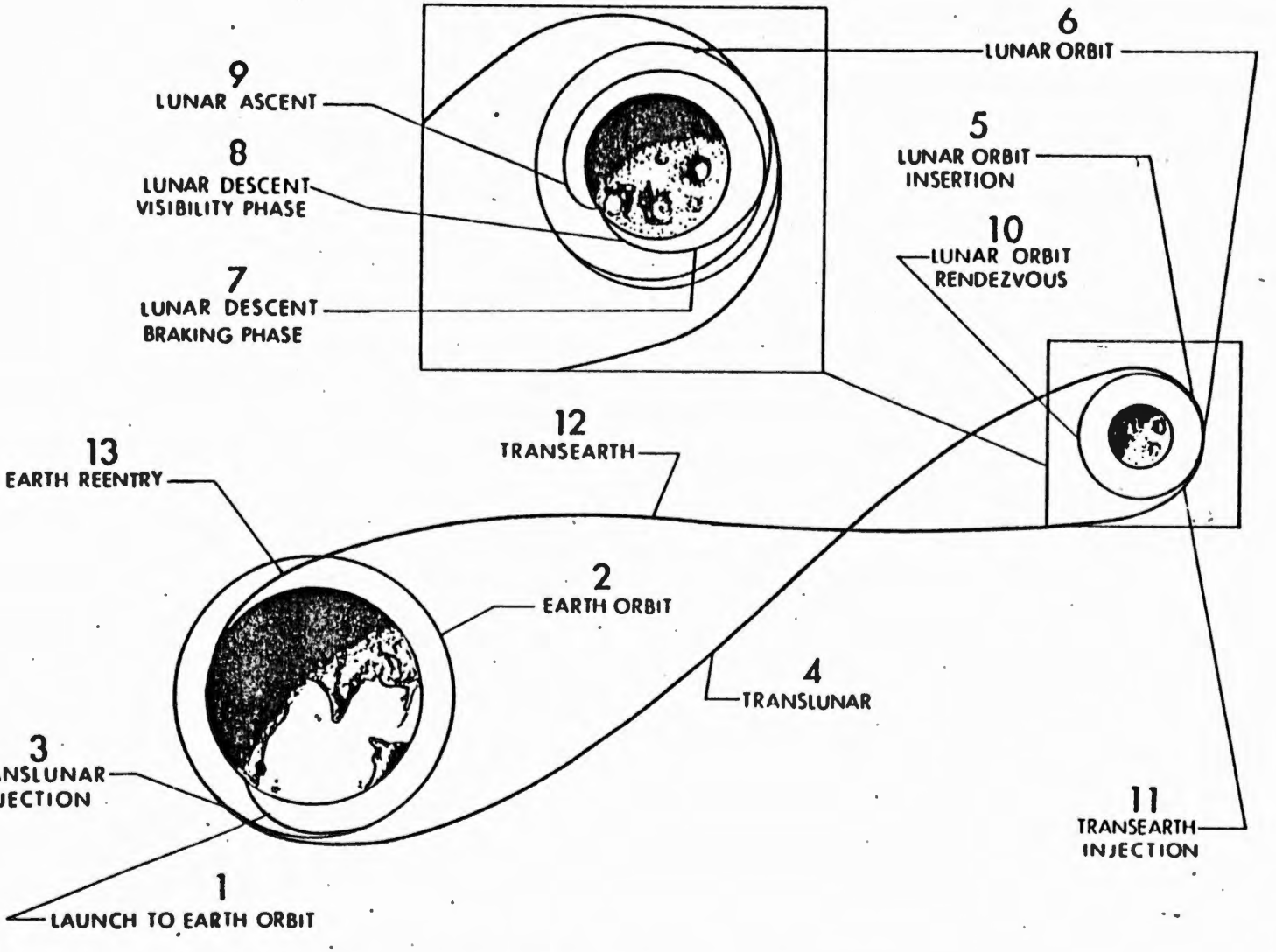

Figure 2.2-1 G&N Mission-Phase Summary

PGNCS CONFIGURATION

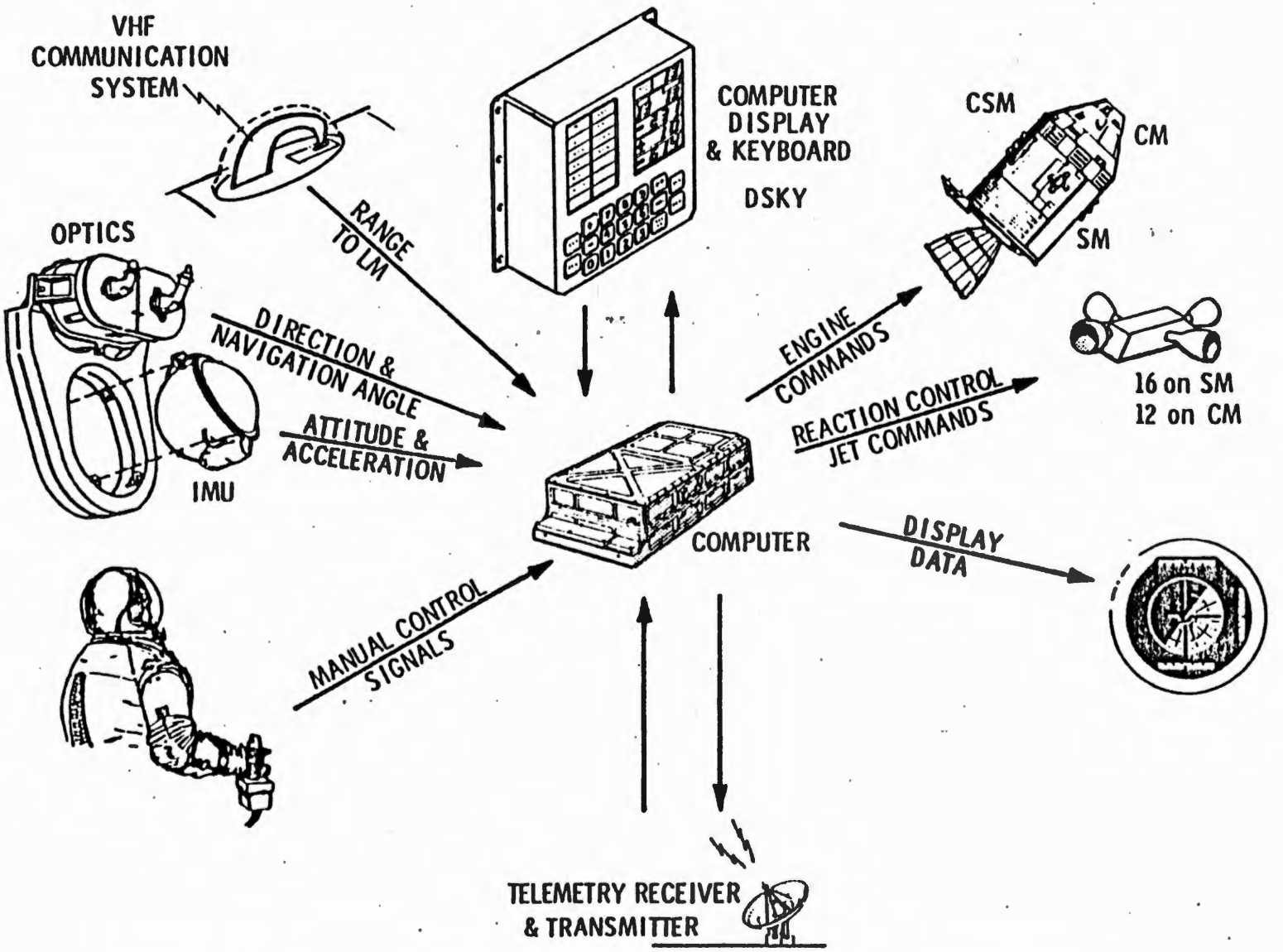

Figure 2-1 COMMAND MODULE GUIDANCE, NAVIGATION AND CONTROL

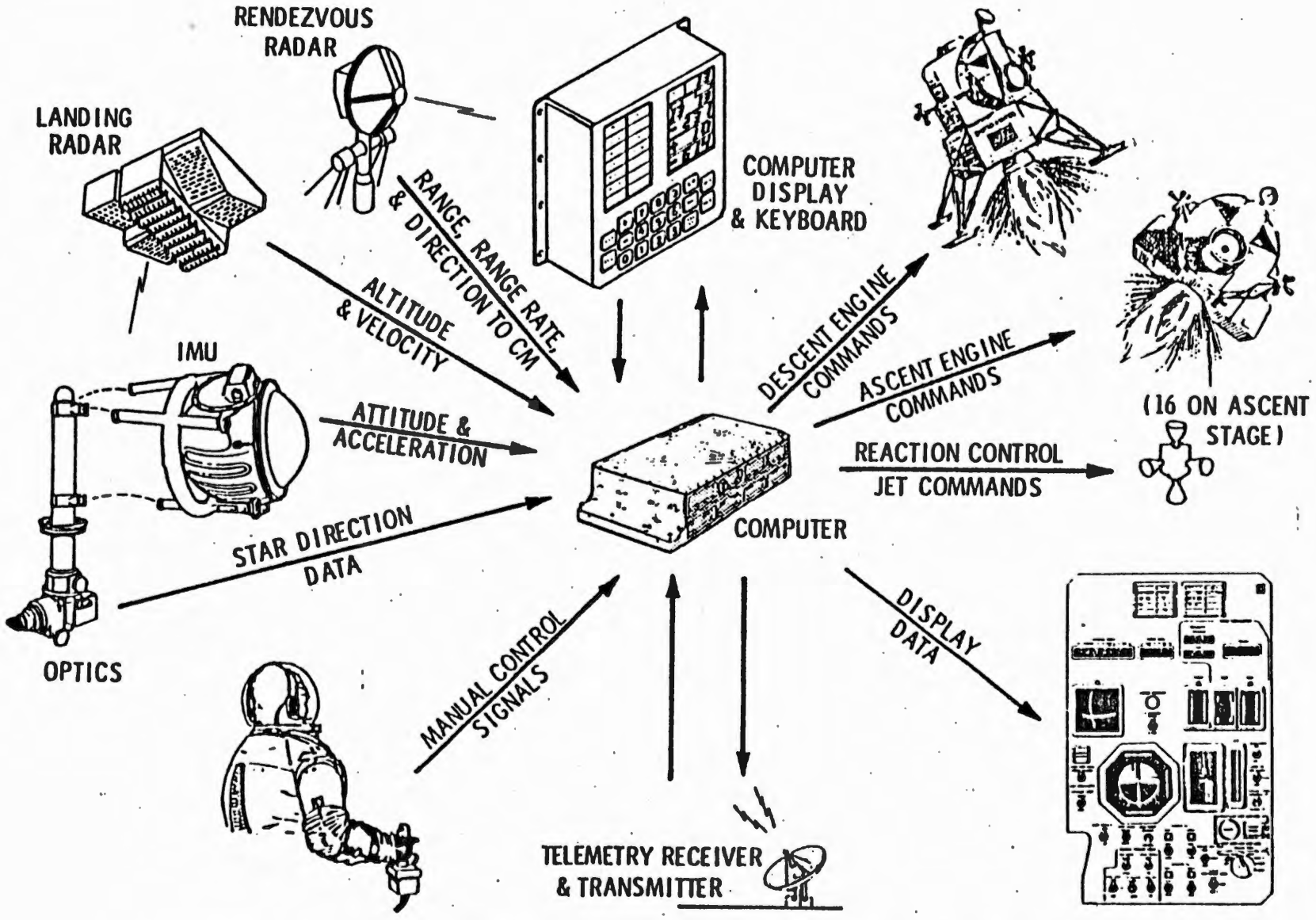

Figure 2-2 LUNAR MODULE GUIDANCE, NAVIGATION AND CONTROL

Computer Characteristics:

- Storage & Manipulation of Data
  - Two types of memory:
    Fixed - 36,864 words
    Erasable - 2048 words
  - Word length - 15 bits data + parity bit
  - Memory Cycle Time - 11.7 μ sec.
  - Machine instructions - 34
  - Software coded in machine language plus "interpretive language"
- Timing & Control
  - Real time operation
  - Time sharing of multiple tasks
  - Priority driven system with interrupts

- Interfaces
  - Counters & Channels
  - Cockpit Displays & Controls
  - Pinball and DSKY (Display & Keyboard)
  - Uplink & Downlink
- Error Detection - Causes:
  - H/W Restarts
  - S/W Restarts

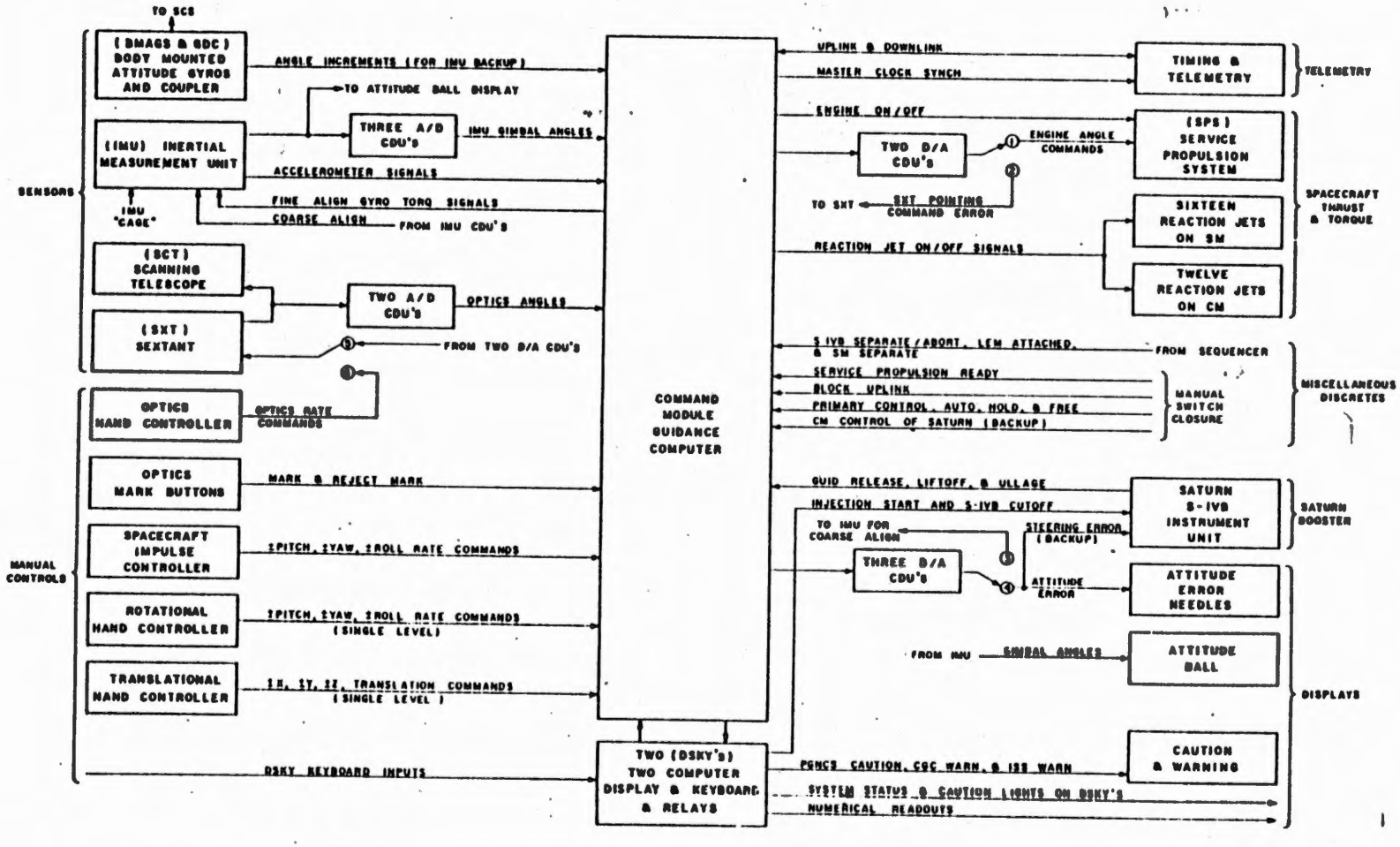

Figure 2.1-1 Guidance, Navigation and Control Interconnections in the Command Module

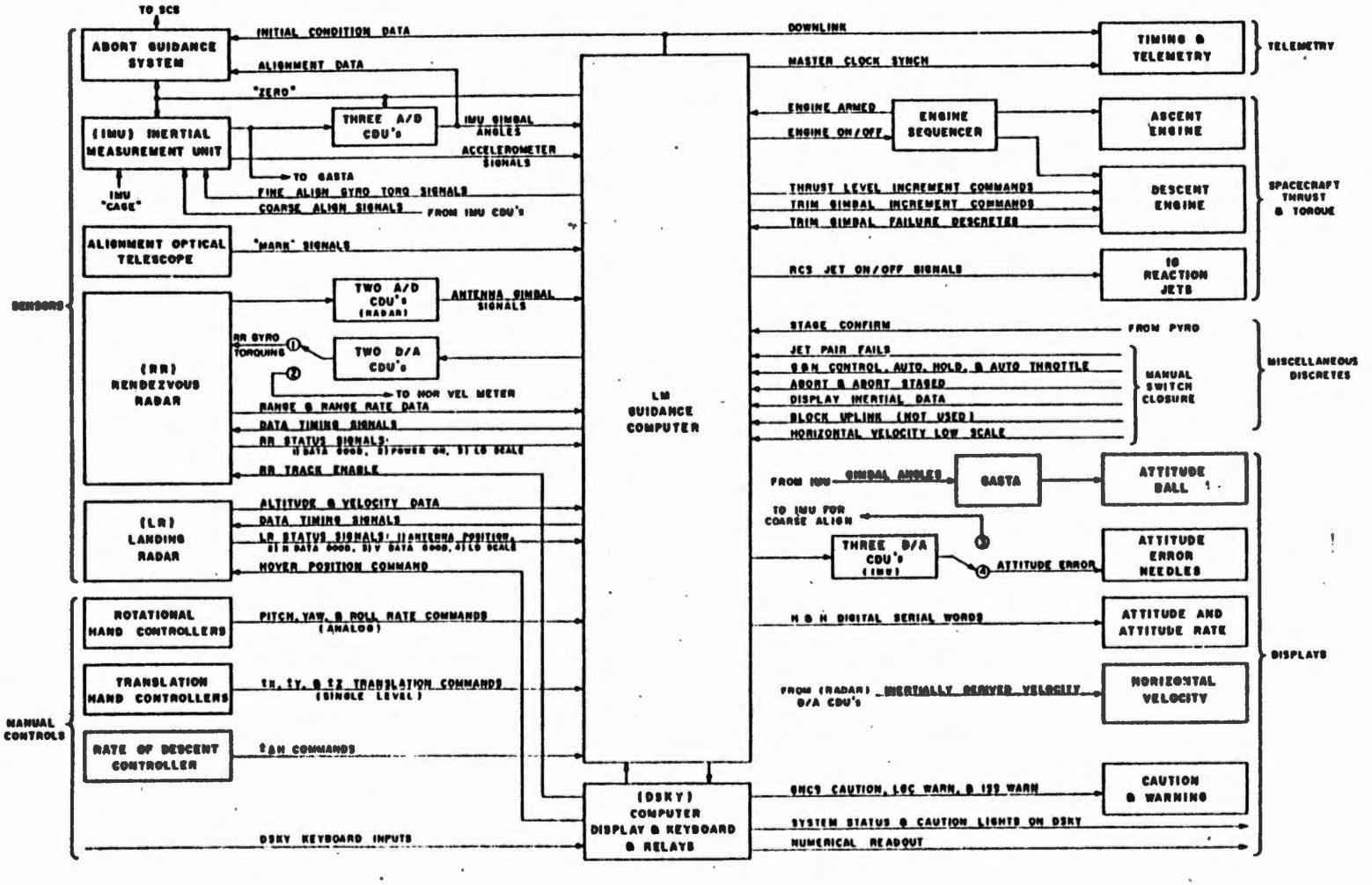

Figure 2.1-2 Guidance, Navigation and Control Interconnections in the Lunar Module

MAN-MACHINE INTERFACE

- S/C Switches & Controllers (Rotation, Translation)
- Display & Keyboard - DSKY

  Programs - Routines

  Verbs

  Nouns

  Decimal & Octal Numerics

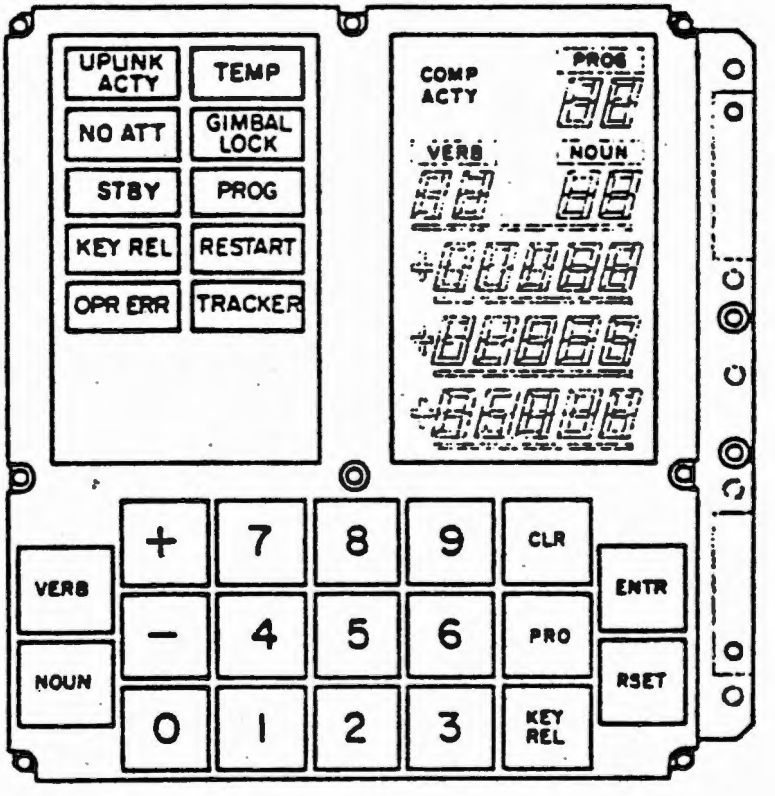

Figure 2-3 DISPLAY AND KEYBOARD

Command Module AGC Programs		Lunar Module AGC Programs	
00	CMC* Idling	00	LGC** Idling
01	Prelaunch Initialization	06	GNCS Power Down
02	Gyro Compassing		
03	Verify Gyro Compassing	12	Powered Ascent Guidance
06	CMC Power Down		
07	IMU Ground Test	20	Rendezvous Navigation
		21	Ground Track Determination
11	Earth Orbit Insertion (EOI) Monitor	22	Lunar Surface Navigation
17	Transfer Phase Initiation (TPI) Search	25	Preferred Tracking Attitude
		27	LGC Update
20	Rendezvous Navigation		
21	Ground Track Determination	30	External ΔV
22	Orbital Navigation	31	Lambert Aimpoint Maneuver
23	Cislunar Midcourse Navigation	32	Coelliptic Sequence Initiation (CSI)
27	CMC Update	33	Constant Delta Height (CDH)
		34	Transfer Phase Initiation (TPI)
30	External ΔV	35	Transfer Phase Midcourse (TPM)
31	Lambert Aimpoint Maneuver	38	Stable Orbit Rendezvous (SOR)
32	Coelliptic Sequence Initiation (CSI)	39	Stable Orbit Midcourse (SOM)
33	Constant Delta Height (CDH)		
34	Transfer Phase Initiation (TPI)	40	DPS
35	Transfer Phase Midcourse (TPM)	41	RCS
37	Return to Earth (RTE)	42	APS
38	Stable Orbit Rendezvous (SOR)	47	Thrust Monitor
39	Stable Orbit Midcourse (SOM)		
		51	IMU Orientation Determination
40	SPS	52	IMU Realign
41	RCS	57	Lunar Surface Align
47	Thrust Monitor		
		63	Braking Phase
51	IMU Orientation Determination	64	Approach Phase
52	IMU Realign	65	Landing Phase (Auto)
53	Backup IMU Orientation Determination	66	Landing Phase (ROD)
54	Backup IMU Realign	67	Landing Phase (Manual)
		68	Landing Confirmation
61	Maneuver to CM/SM Separation Attitude		
62	CM/SM Separation & Preentry Maneuver	70	DPS Abort
63	Entry-Initialization	71	APS Abort
64	Entry-Post 0.05 g	72	CSM CSI Targeting
65	Entry-Up Control	73	CSM CDH Targeting
66	Entry-Ballistic	74	CSM TPI Targeting
67	Entry-Final Phase	75	CSM TPM Targeting
		76	Target ΔV
72	LM Coelliptic Sequence Initiation (CSI)	78	CSM SOR Targeting
73	LM Constant Delta Height (CDH)	79	CSM SOM Targeting
74	LM TPI Targeting		
75	LM TPM Targeting		
76	Target ΔV		
77	LM TPI Search		
78	LM SOR Targeting		
79	LM SOM Targeting		

*CMC is Command Module Computer (CM AGC)

**LGC is Lunar Guidance Computer (LM AGC)

Figure 2.1-4 Programs for a Lunar-Landing Mission

THIS LIST REPRESENTS THE VERBS USED IN PROGRAM COLOSSUS

REGULAR VERBS

00 NOT IN USE
01 DISPLAY OCTAL COMP 1 IN R1
02 DISPLAY OCTAL COMP 2 IN R1
03 DISPLAY OCTAL COMP 3 IN R1
04 DISPLAY OCTAL COMP 1,2 IN R1,R2
05 DISPLAY OCTAL COMP 1,2,3 IN R1,R2,R3
06 DISPLAY DECIMAL IN R1 OR R1,R2 OR R1,R2,R3
07 DISPLAY DP DECIMAL IN R1,R2
08 SPARE
09 SPARE
10 SPARE
11 MONITOR OCTAL COMP 1 IN R1
12 MONITOR OCTAL COMP 2 IN R1
13 MONITOR OCTAL COMP 3 IN R1
14 MONITOR OCTAL COMP 1,2 IN R1,R2
15 MONITOR OCTAL COMP 1,2,3 IN R1,R2,R3
16 MONITOR DECIMAL IN R1 OR R1,R2 OR R1,R2,R3
17 MONITOR DP DECIMAL IN R1,R2
18 SPARE
19 SPARE
20 SPARE
21 LOAD COMPONENT 1 INTO R1
22 LOAD COMPONENT 2 INTO R2
23 LOAD COMPONENT 3 INTO R3
24 LOAD COMPONENT 1,2 INTO R1,R2
25 LOAD COMPONENT 1,2,3 INTO R1,R2,R3
26 SPARE
27 DISPLAY FIXED MEMORY
28 SPARE
29 SPARE
30 REQUEST EXECUTIVE
31 REQUEST WAITLIST
32 RECYCLE
33 PROCEED
34 TERMINATE
35 TEST LIGHTS
36 REQUEST FRESH START
37 CHANGE PROGRAM
38 SPARE
39 SPARE

EXTENDED VERBS

40 ZERO CDU
41 COARSE ALIGN CDU (W N20,N91)
42 PULSE TORQUE GYRO
43 LOAD FDAI ATT ERROR NEEDLES (TEST ONLY)
44 SET SURFACE FLAG
45 RESET SURFACE FLAG
46 ACTIVATE CAP
47 SET LM STATE VECTOR INTO CSM STATE VECTOR
48 LOAD DAP DATA (R03)
49 START CREW DEFINED MANEUVER (R62)

Figure 2.1-5 Verbs Used in Program COLOSSUS

THIS LIST REPRESENTS THE NOUNS USED IN PROGRAM COLOSSUS.

00	NOT IN USE	
01	SPECIFY ADDRESS (FRAC)	.XXXXX FRAC .XXXXX FRAC .XXXXX FRAC
02	SPECIFY ADDRESS (WHOLE)	XXXXX. INTEG XXXXX. INTEG XXXXX. INTEG
03	SPECIFY ADDRESS (DEGREE)	XXX.XX DEG XXX.XX DEG XXX.XX DEG
04	SPARE	
05	ANGULAR ERROR/DIFFERENCE	XXX.XX DEG
06	OPTION CODE	OCT OCT
07	CHANNEL/FLAGWORD/ERASABLE OPERATOR	OCT OCT OCT
08	ALARM DATA	OCT OCT OCT
09	ALARM CODES	OCT OCT OCT
10	CHANNEL TO BE SPECIFIED	OCT
11	TIG OF CSI	00XXX. HRS 000XX. MIN 0XX.XX SEC
12	OPTION CODE	OCT OCT
13	TIG OF CDH	00XXX. HRS 000XX. MIN 0XX.XX SEC
14	SPARE	
15	INCREMENT ADDRESS	OCT
16	TIME OF EVENT (USED BY EXT VERB ONLY)	00XXX. HRS 000XX. MIN 0XX.XX SEC
17	ASTRONAUT TOTAL ATTITUDE (USED IN MODE 3 NEEDLES (V63))	XXX.XX DEG XXX.XX DEG XXX.XX DEG
18	BALL ANGLES AUTO MANEUVER	R XXX.XX DEG P XXX.XX DEG Y XXX.XX DEG
19	SPARE	
20	PRESENT ICDU ANGLES	R XXX.XX DEG P XXX.XX DEG Y XXX.XX DEG
21	PIPAS	X XXXXX. PULSES Y XXXXX. PULSES Z XXXXX. PULSES
22	NEW ICDU ANGLES	R XXX.XX DEG P XXX.XX DEG Y XXX.XX DEG
23	SPARE	
24	DELTA TIME FOR CMC CLOCK	00XXX. HRS 000XX. MIN 0XX.XX SEC
25	CHECKLIST (USED WITH V50)	XXXXX.
26	PRIO/DELAY,ADRES,R8CON	OCT OCT OCT
27	SELF TEST ON/OFF SWITCH	XXXXX.
28	SPARE	
29	XSM LAUNCH AZ	XXX.XX DEG
30	TARGET CODE (GYRCOMPASSING VERIFICATION)	XXXXX. XXXXX. XXXXX.
31	SPARE	
32	TIME FROM PERIGEE	00XXX. HRS 000XX. MIN 0XX.XX SEC

Figure 2.1-6 Nouns Used in Program COLOSSUS

SOFTWARE

SPECIFICATION & CONTROL

Software Specification Control Document

- GSOP - Guidance Systems Operations Plans

  consists of the following sections:

  Section 1 Prelaunch

  2 Data links

  3 Digital Autopilots

  4 Operational Modes

  5 Guidance Equations

  6 Control Data

NASA/MSC Software Configuration Control Board

- Responsible for: the control of all GSOPs, all changes of GSOPs, programs placed under configuration control at the First Article Configuration Inspection (FACI)

- Has authority to approve waivers of software requirements

- SCB Membership

  Flight Operations Directorate, Chairman
  ASPO CSM Engineering
  ASPO LM Engineering
  Guidance and Control Division
  Flight Crew Support Division
  Mission Planning and Analysis Division
  Flight Control Division
  Flight Support Division
  Flight Crew Operations Division
  Bellcomm
  ASPO Guidance and Propulsion

- Change Instruments:

  Program Change Request - PCR

  Contents:

  ORIGINATOR

  EFFECTIVITY

  REASON FOR CHANGE

  DEFINITION OF CHANGE

  SCB DECISION FOR VISIBILITY IMPACT

  MIT IMPACT EVALUATION

  SCB Action

  MIT DETAILED EVALUATION

  SCB ACTION

- Program Change Notice - PCN

  NOTIFICATION OF CLERICAL CORRECTION

  OR

  NOTIFICATION OF MANDATORY CHANGE TO PERMIT FURTHER PROGRAM DEVELOPMENT

- Anomaly Report - Deviations (differences) between software code and Specification

- Assembly Control Board Request

  MIT/IL initiated change that did not change the specification

IMPLEMENTATION & CONTROL

S/W Development

Small group initially laid out the S/W Structure - operation system, executive, input/output, Program, Routine, Verb-Noun concepts to support H/W development and testing. As project became more mission oriented and a small group was no longer adaquate to perform the job, planning and controlling became more of a requirement.

Date 3/17/71

MIT/CSDL SOFTWARE DEVELOPMENT PLAN
FOR
LUMINARY 1E LGC PROGRAM

R.H. Larson 3-23-71
LUMINARY Project Manager's Signature — Date

for R.H. Battin 3/23/71
Director Mission Development Approval — Date

This plan consists of 28 pages

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MIT/IL Mission Design Review Board (MDRB)

Controlled all mission related documentation and the incorperation of requirements into the Mission programs.

MDRB membership:

Project Manager, Chairman
System Test Division Director
Systems Engineering Division
Autopilot Development Group Leader
Guidance Analysis Division Director
Display & Human Factors Division Director
NASA/FSB (Flight S/W Branch) Program Engineers

Mission Program Change Board (MPCB)

Responsible for review and implementation of each change candidate.

Staffing:

Mission Program Integration Director, Chairman

Mission Project Managers

Program Supervisors

Program Development Chief Engineers

Assembly Control Group Leader

Supporting staff as assigned by above

Other division representation as requested

Storage Committe:

Maintained assignment of fixed and erasable memory.

Assembly Control Group

Has full time responsibility for the making and the control of all official assemblies. All changes funnel through this group (person).

Developmental Milestones

PDR - Preliminary Design Review

CDR - Critical Design Review

FACI - First Article Configuration Inspection

- Level 3 & 4
- NASA configuration control

CARR - Customer Acceptance Readiness Review

- Level 5 complete
- Release for rope manufacture

FSRR - Flight Software Readiness Review

- Level 6 complete
- S/W test facilities report

FRR - Flight Readiness Review

Testing, Verification, Validation

- Philosophy - Bottom Up - 6 Levels
- Two major areas of testing - computation and logic
- Comprehensive test plan is key
- Designers - designed and evaluated testing - not an independent test group
- Testing tracked by Development and Mission Support Plans.

Levels of Testing

Level 1 tests were high order language (HOL) programs run on the host computer to test algorithms. The MAC (MIT Algebraic Compiler), developed at MIT/IL, was used for this effort.

Level 2 was the AGC counterpart of these programs. The results of the two were compared to establish the accuracy of the AGC equivalent. The errors found at this level were primarily computational.

Level 3 was intended to verify the operation of a complete program or routine including crew interface and realistic physical environment models. The errors discovered at this level were primarily logic and display interface problems. This level was performed only when a routine was incorporated into the flight program.

Level 4 testing was intended to verify mission phases, e.g., ascent, rendezvous. The multi-programmed environment was exercised extensively and therefore uncovered priority, timing, and erasable-sharing problems.

LEVEL 5 REPEATED THE LEVEL 4 TESTS ON THE FINAL ROPE WHICH WAS RELEASED FOR MANUFACTURE. THIS WAS REQUIRED BECAUSE EVEN THOUGH THE LEVEL 4 TESTS HAD BEEN SUCCESSFULLY COMPLETED, THEY MAY NOT HAVE RUN ON THE VERSION OF THE PROGRAM THAT WAS RELEASED.

LEVEL 6 TOOK PLACE AFTER THE ROPES WERE RELEASED FOR MANUFACTURE AND WERE INTENDED TO VERIFY THE PROGRAM USING ACTUAL MISSION DATA AND THE FLIGHT TIME-LINE. THESE RUNS WERE RUN WITH 1 SIGMA AND 3 SIGMA ERRORS IN THE SIMULATED INSTRUMENTS.

TESTING TOOLS/SIMULATORS

ALL DIGITAL SIMULATOR

ENGINEERING SIMULATIONS

HYBRID SIMULATORS

SYSTEM TEST LABORATORY

Again the S/W Development Plan

&

Mission Support Plan

Date 3 April 1970

MIT/CSDL MISSION SUPPORT DEVELOPMENT PLAN

FOR MISSION "H-2"

(APOLLO 13)

LUMINARY 1C
(FINAL ISSUE)

Ronald H Larson 4-3-70

LUMINARY Project Manager's Signature — Date

R H Battin for 4-3-70

Director, Mission Development Approval — Date

This plan consists of 33 pages.

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LM PROGRAM DEVELOPMENT SUMMARY DATE 4/3/70

ITEM NO.	DESCRIPTION	NOTE	PREDICTED DATE	ORIGINAL TARGET	ACTUAL DATE	REQUIRED DATES	SCHEDULED REV. DATE	RESI ENGINI
1	FLIGHT PROGRAM							
	LUMINARY 130			11/5/69	11/5/69			
	LUMINARY 131			12/3/69	12/3/69			
	Rev 9 (PCR 988 "Auto P66" Implemented)				1/14/70			
	LM131 Rev 1 (PCR 1013)			2/9/70	2/4/70			
	FSRR		3/16/70	3/11/70	3/16/70			
2	GSOP Status		See GSOP Status Pages					
3	Level 6 Performance Test Plan			12/2/69	12/4/69			
4	Level 6 AGC Performance Testing							
	Start		2/13/70	2/13/70	2/13/70			
	Completion		2/27/70	2/27/70	2/27/70			
	Documentation		3/6/70	3/4/70	3/12/70			
5	RTCC Compatibility Testing							
	Documentation		3/6/70	3/4/70	3/13/70			
6	Mission Procedural Test Plan		11/26/69	11/26/69	11/26/69			
7	Mission Procedural Verification Testing							
	Start		12/19/69	12/19/69	1/8/70			
	Completion		3/30/70	2/23/70				
	Documentation		4/3/70	3/4/70				
8	System Test Lab Testing							
	Level 5 Start		11/10/69	11/10/69	11/10/69			
	Completion		12/12/69	12/12/69	12/12/69			
	Documentation		12/19/69	2/4/70	12/31/69			
9	MIT Deliverable Items							
	K-Start Tape Schedule		12/31/69	12/31/69	12/31/69			

MIT/IL REVIEW OF NASA/MSC DOCUMENTATION

DATE 4/3/70

ITEM NO.	DESCRIPTION		NASA ISSUE DATE		MIT REC'D. DATE	MIT REVIEW COMPLETION		COMMENTS
			Pred.	Actual	Actual	Pred.	Actual	
I.	Flight Data File							
	a) LM Timeline Book	Preliminary	2/16	2/16	2/25	3/16	3/16	
		Final	3/23					
	b) LM Data Card Book	Preliminary	1/12	1/12	1/19	2/16	2/16	
		Final	3/16					
	c) LM Systems Activation Checklist	Preliminary	2/2	2/6	2/19	3/9	3/9	
		Final	3/16					
	d) LM G&N Dictionary	Preliminary	1/5	1/5	1/19	2/16	2/16	
		Final	3/9					
	e) LM Contingency Checklist	Preliminary	2/2	1/23	1/29	2/23	2/23	
		Final	3/9					
	f) LM Lunar Surface Checklist	Preliminary	2/16	2/16	2/20	3/16	3/16	
		Final	3/23					
	g) LM Cue Cards	Preliminary	1/19	1/19	1/23	2/23	2/23	
		Final	3/23					
	h) LM Systems Data	Preliminary	1/19	1/19	1/23	2/23	2/23	
		Final	3/9					
	i) LM Malfunction Procedures	Preliminary	1/19	2/6	2/17	3/9	3/9	
		Final	3/9					
	j) LM Rendezvous Charts	Preliminary	1/19	1/5	1/9	2/16	2/16	
		Final	3/9					

GSOP STATUS

DATE 4/3/70

DESCRIPTION	BLUE COVER DISTRIBUTION			PROGRAM	COMMENTS
	Predicted Date	Original Date	Actual Date		
Section 1 - Prelaunch					
Rev 1	1/17/69	12/23/68	1/29/69		
Section 2 - Data Links					
Rev 5	8/28/69	8/1/69	9/12/69	LNY 1B	Change Pages
Rev 6	10/29/69		11/4/69	LNY 1B	Change Pages
Rev 7	11/17/69	11/17/69	11/19/69	LNY 1C	
Rev 8	4/10/70			LNY 1C	Change Pages (See no
Section 3 - Digital Autopilot					
Rev 2	8/28/69	8/12/69	8/29/69	LNY 1B	Change Pages
Rev 3	12/15/69	11/15/69	12/15/69	LNY 1C	
Rev 4	4/10/70			LNY 1C	Change Pages (See no
Section 4 - Operational Modes					
Rev 5	8/19/69	8/1/69	8/22/69	LNY 1B	
Rev 6	9/26/69	9/26/69	10/8/69	LNY 1B	Change Pages
Rev 7	12/23/69	11/15/69	12/30/69	LNY 1C	
Rev 8	4/30/70			LNY 1C	Change Pages (See no
Section 5 - Guidance Equations					
Rev 5	8/12/69	8/1/69	8/15/69	LNY 1B	
Rev 6			10/23/69	LNY 1B	Change Pages
Rev 7	12/8/69	11/15/69	12/15/69	LNY 1C	
Rev 8	4/10/70			LNY 1C	Change Pages (See no
Section 6 - Control Data					
Rev 0	9/3/68	2/1/68	12/9/68	LNY 1	

NOTE: Change pages for PCRs 942, 988 and 1013

LEVEL 6 LM PERFORMANCE TEST DESCRIPTION DATE 4/3/70

TEST	DESCRIPTION	RESPONSIBLE ENGINEER
6.1.0	Rendezvous	White
6.1.1	Nominal LM Active w/P52 Alignment	White
6.2.0	Aborts from Descent	Bernikovich
6.2.1	Abort at 30K ft-Insertion to CSI Solution w/P20 Navigation.	Bernikovich
6.2.2	Abort at 7K ft-Insertion to CSI Solution w/P20 Navigation.	Bernikovich
6.2.3	Abort after Touchdown-Insertion to CSI Solution w/P20 Navigation.	Bernikovich
6.2.4	Abort at 46K ft.	Bernikovich
6.2.5	Abort Stage at 46K ft.	Bernikovich
6.3.0	Lunar Surface Operation and Ascent	Millard
6.3.1	(Offset RLS to show effect of gravity vector updates to RLS) (Initialized with 5^{o} pitch, 15^{o} yaw) P68 P00, P12, P57 (2 stars), P06, P57 (gravity/star), P57 (gravity/REFSMMAT) P22, P12, P20, P32	Millard
6.4.0	Landing (Prime Site)	Moore
6.4.1	Automatic Landing - V59 just Prior to HIGATE	Moore
6.4.2	P66 Landing with following Redesignations N69: 10K/5K ft; ACA; none N69: 20K/20K ft; ACA: 2 + AZ/2 - EL N69: None; ACA: 2 - AZ/2 + EL	Moore

LUMINARY 1C

PERFORMANCE TESTING

4/3/70

LM131 Rev 1 Level 4 TLOSS		5% TLOSS Level 6		
		LUMINARY 131	LUM131 Rev 9	LM131 Rev 1
	Rendezvous			
5%	Nominal LM Active w/P52 Alignment	X	X	X
	Aborts from Descent			
	Abort at 30K ft-Insertion to CSI Solution w/P20 Navigation	X	X	X
5%	Abort at 7K ft-Insertion to CSI Solution w/P20 Navigation	X	X	X
	Abort after Touchdown - Insertion to CSI Solution w/P20 Navigation	X	X	X
9.5%	Abort at 46K-ft			X
	Abort Stage at 46K-ft			X
	Lunar Surface Operation and Ascent			
	(Offset RLS to Show Effect of Gravity Vector Updates to RLS)			
	(Initialized with 5° Pitch, 15° Yaw)			
5%	P68, P00, P12, P57 (2 Stars), P06, P57 (Gravity/Star)			
	P57 (Gravity/REFSMMAT), P22, P12, P20, P32		X	X
	Landing (Prime Site)			
	Automatic Landing - V59 just Prior to HIGATE	X	X	X
5%	P66 Landing with Following Redesignations			
	N69: 10K/5K ft; ACA: None	X	X	X
9.5%	N69: 20K/20K ft; ACA: 2 + AZ/2 - EL	X	X	X
	N69: None; ACA: 2 - AZ/2 + EL	X	X	X

LM LEVEL 6 PERFORMANCE TEST STATUS

DATE 4/3/70

TEST	PRIMARY SETUP INPUT PREPARED						ALL RUNS COMPLETED AND RESULTS EVALUATED			SUMMARY MATERIA PREPARED		
	Req.	Pred.	Actual				Req.	Pred.	Actual	Req.	Pred.	Actu
6.1.1	2/13	2/13	2/13				2/27	2/27	2/22	3/6	3/6	3/12
6.2.1	2/13	2/13	2/13				2/27	2/27	2/22	3/6	3/6	3/12
6.2.2	2/13	2/13	2/13				2/27	2/27	2/22	3/6	3/6	3/12
6.2.3	2/13	2/13	2/13				2/27	2/27	2/22	3/6	3/6	3/12
6.2.4	2/13	2/13	2/13				2/27	2/27	2/22	3/6	3/6	3/12
6.2.5	2/13	2/13	2/13				2/27	2/27	2/22	3/6	3/6	3/12
6.3.1	2/13	2/13	2/13				2/27	2/27	2/27	3/6	3/6	3/12
6.4.1	2/13	2/13	2/13				2/27	2/27	2/27	3/6	3/6	3/12
6.4.2	2/13	2/13	2/13				2/27	2/27	2/22	3/6	3/6	3/12

"H-2" MISSION RTCC/LUMINARY 1C COMPATIBILITY TESTING Date 4/3/70

TEST No.	TEST DESCRIPTION	Responsible Engineer
H2LRTCC.1	APS Abort (P30/P42)	Kirven
H2LRTCC.2	DPS Abort (P30/P40)	Kirven
H2LRTCC.3	Uplink Test (all LGC Command Loads)	Finkelstein
H2LRTCC.4	NOM CSI (P32)	White
H2LRTCC.5	Preturbed CDH (P33)	White
H2LRTCC.6	Preturbed TPI (P34)	White
H2LRTCC.7	Preturbed TPI (P34)	White
H2LRTCC.8	Two Star Alignment (P57)	Millard
H2LRTCC.9	Star/g-vector Alignment (P57)	Millard

"H-2" MISSION RTCC/LUMINARY 1C COMPATIBILITY TESTING Date 4/3/70

TEST No.	Supply RTCC Data			Complete Summary Edit Changes			Receive RTCC Data			Begin Simulations			Deliver Data Package		
	Due	Pred	Act	Due	Pred	Act	Due	Pred	Act	Due	Pred	Act	Due	Pred	A
H2LRTCC.1	1/1/70	12/20	12/20	1/5	1/5	1/5	1/20	1/20	1/20	1/27	1/27	1/27	2/11	3/11	3/
H2LRTCC.2	1/1/70	12/20	12/20	1/5	1/5	1/5	1/20	1/20	1/20	1/27	1/27	1/27	2/11	3/11	3/
H2LRTCC.3	NA	12/20	12/20	1/5	1/5	1/5	1/20	1/20	1/20	1/27	1/27	1/27	2/11	3/11	3/
H2LRTCC.4	NA	12/20	12/20	1/5	1/5	1/5	1/20	1/20	1/20	1/27	1/27	1/27	2/11	2/11	2/
H2LRTCC.5	NA	12/20	12/20	1/5	1/5	1/5	1/20	1/20	1/20	1/27	1/27	1/27	2/11	2/11	2/
H2LRTCC.6	NA	12/20	12/20	1/5	1/5	1/5	1/20	1/20	1/20	1/27	1/27	1/27	2/11	2/11	2/
H2LRTCC.7	NA	12/20	12/20	1/5	1/5	1/5	1/20	1/20	1/20	1/27	1/27	1/27	2/11	2/11	2/
H2LRTCC.8	NA	12/20	12/20	1/5	1/5	1/5	1/20	1/20	1/20	1/27	1/27	1/30	2/11	2/11	2/
H2LRTCC.9	NA	12/20	12/20	1/5	1/5	1/5	1/20	1/20	1/20	1/27	1/27	1/30	2/11	2/11	2/

MISSION PROCEDURAL VERIFICATION DATE 4/3/70

MPV TEST	SEQUENCE DESCRIPTION	MISSION "H-2" PROGRAM LUMINARY 1C LM131 Rev 1	RESPONSIBLE ENGINEER
2.1A	Docked DPS DOI ABORT (not to be completed)		
2.1B	Docked APS DOI ABORT (not to be completed)		
3.3A	PDI (50,000') to Landing - Auto		
3.3B	PDI (50,000') to Landing - ROD		
3.3C	PDI (50,000') to Landing - Redesignate		
3.31A	PDI (30,000') to Landing - Auto		
3.31B	PDI (30,000') to Landing - ROD		
3.31C	PDI (30,000') to Landing - Redesignate		
3.32A	PDI (70,000') to Landing - Auto		
3.32B	PDI (70,000') to Landing - ROD		
3.32C	PDI (70,000') to Landing - Redesignate		
3.4A	DPS Abort from Descent (PDI at 50,000')		
3.4B	DPS-APS Abort from Descent (PDI at 50,000')		
3.41A	DPS Abort from Descent (PDI at 30,000')		
3.41B	DPS-APS Abort from Descent (PDI at 30,000')		
3.42A	DPS Abort from Descent (PDI at 70,000')		
3.42B	DPS-APS Abort from Descent (PDI at 70,000')		
3.43A	DPS Abort from 2nd Pass Descent (PDI at 30,000') (not to be completed)		
3.43B	DPS-APS Abort from 2nd Pass Descent (PDI at 30,000') (not to be completed)		

LEVEL V SYSTEM TEST LAB TESTS OF LUMINARY 1C (LUM131) Date 4/3/70

TEST	TITLE	ENGINEER	Test Complete			Document Approv		
			Req	Pred	Act	Req	Pred	Ac
STP2	IMU Performance Test	Grace			11/28		12/12	12/
STP3	IRIG SF Test	Grace			11/28		12/12	12/
STP5	AGS Align Test	St. Amand			12/12		12/19	12/
RP	Radar Test	Reedy			12/12		12/19	12/

LUMINARY 1C FLOW CHART SCHEDULE DATE 4/3/70

ITEM NO	DESCRIPTION	RESPONSIBILITY	DISTRIBUTION		
			Required	Predicted	Actua
1	Interbank Communication	Danforth		12/22/69	1/5/70
2	Display Interface Routines	Danforth		———	
3	Extended Verbs	Danforth		12/22/69	1/5/70
4	KEYRUPT and UPRUPT	Entes		12/8/69	11/5/69
5	Alarm and Abort	Beck		12/8/69	1/5/70
6	Single Prec. Subroutines	Entes		11/7/69	11/5/69
7	T4RUPT	Entes		2/20/70	2/9/70
8	IMU Compensation Package	J.B. Smith		4/13/70	
9	R04, R77	Danforth		12/22/69	1/5/70
10	In-flight Alignment Routine	J.B. Smith		1/26/70	1/26/7
11	Lunar and Solar Ephemerides	Danforth		12/8/69	11/5/69
12	Integration Initialization	Danforth		12/22/69	1/5/70
13	Time of Free Fall	Entes		3/9/70	3/19/7
14	R05	Danforth		12/22/69	1/5/70
15	DAP Interface	Entes		3/27/70	
16	LM RCS DAP	Entes		3/27/70	
17	LM DAP Gimbal Trim	Entes		11/24/69	11/14/6
18	AOSJOB and AOSTASK	Entes		3/27/70	3/19/7
19	P52	Reed		3/27/70	3/19/7
20	P20, P22	Danforth		12/22/69	1/5/70
21	P21	Danforth		11/21/69	11/5/69
22	P76 Target Delta V	Entes		1/26/70	1/26/7
23	P34-P74 TPI	Danforth		12/22/69	1/5/70
24	R30 Orbital Parameters Display	Entes		12/8/69	11/5/69
25	R36	Entes		12/22/69	1/5/70

USER'S GUIDE STATUS REPORT DATE 4/3/70

ITEM NO.	DESCRIPTION	RESPONSIBILITY	DISTRIBUTION		COMMENTS
			Predicted	Actual	
1.	SERVICE				
	P00 - LGC Idling	J.B. Smith			
	P06 - LGC Power Down	J.B. Smith			
2.	ASCENT				
	P12 - Powered Ascent	Wolff	11/17/69	11/17/69	
3.	COAST				
	P20 - Rendezvous Navigation	Reed	1/19/70	1/21/70	
	P21 - Ground Track Determination	Hubbard	1/5/70	1/7/70	
	P22 - Lunar Surface Navigation	Hubbard	1/19/70	1/28/70	
	P25 - Preferred Tracking Attitude	Slifer	2/7/70		
4.	PRETHRUSTING				
	P30 - External ΔV	J.B. Smith	1/26/70	1/26/70	
	P32 - Co-Elliptic Sequence Initiation (CSI)	J.B. Smith	2/16/70		
	P33 - Constant Delta Altitude (CDH)	J.B. Smith			
	P34 - Transfer Phase Initiation (CSI)	J.B. Smith			

LUMINARY 1C ANOMALY STATUS REPORT DATE 4/3/70

MSC NO.	DESCRIPTION	Originator/ Date/ Control No.	RECOMMENDED DISPOSITION (Date Submitted to NASA)	NASA DIRECTION/ DATE	CLOSING ACTION TAKEN/ DATE
-1B-02	R29 will not achieve RR Lockon.	MIT 8/29/69	Work-around in Luminary 1B; fix in Luminary 1C. 8/25/69	Do not fix for Luminary 1C per SCB 10/9/69.	
-1B-11	Terminal Mass Error.	MIT 10/31/69	Fix for Luminary 1D. 10/31/69		
-1C-01	Delta-V increment may be subtracted twice from V_G, following a restart.	MIT	Fix for Luminary 1D. 11/7/69	Fix for Luminary 1D. 12/15/69	
-1C-02	For early abort from PDI locations of a VAC area are destroyed.	MIT 12/3/69	Fix for Luminary 1C 12/4/69	Fix for Luminary 1C. 12/5/69	Re-release of Program Rev 131.
-1C-03	Routine LRPOS2 is called by a TC, but it returns via SWRETURN.	MIT 12/1/69	Fix for Luminary 1D. 12/4/69	Fix for Luminary 1D. 12/5/69	
-1C-04	Two REMODE tasks operating simultaneously.	MIT 12/19/69	Work-around in Luminary 1C. Fix for Luminary 1D. 12/22/69		
-1C-05	Sign disagreement when HCALC is calculated with RVBOTH.	MIT 1/7/70	Fix for Luminary 1D. Program note for 1C. 1/7/70	Fix for Luminary 1D. Program note for 1C. 1/23/70	
-1C-06	P40, P42, or P63 Commanding Ullage, with Average-g off.	NASA/MSC 1/19/70	Fix for Luminary 1D. Program note for 1C. 2/26/70	Fix for Luminary 1D. 3/18/70	Program note for 1C.
-1C-07	Erroneous State Vector and W-matrix while in P00.	MIT 3/11/70	Fix for Luminary 1D. Program note for 1C. 3/11/70		Further analysis at has shown that this i not an anomaly.

Other Facilities

GAEC -FMES

RI - ME & HE

JSC - CMS, LMS

KSC - CMS

PAD - SIM FLIGHT

Magnitude of Effort

- How much of what
- No. of Releases
- Schedule
- Manpower Requirements

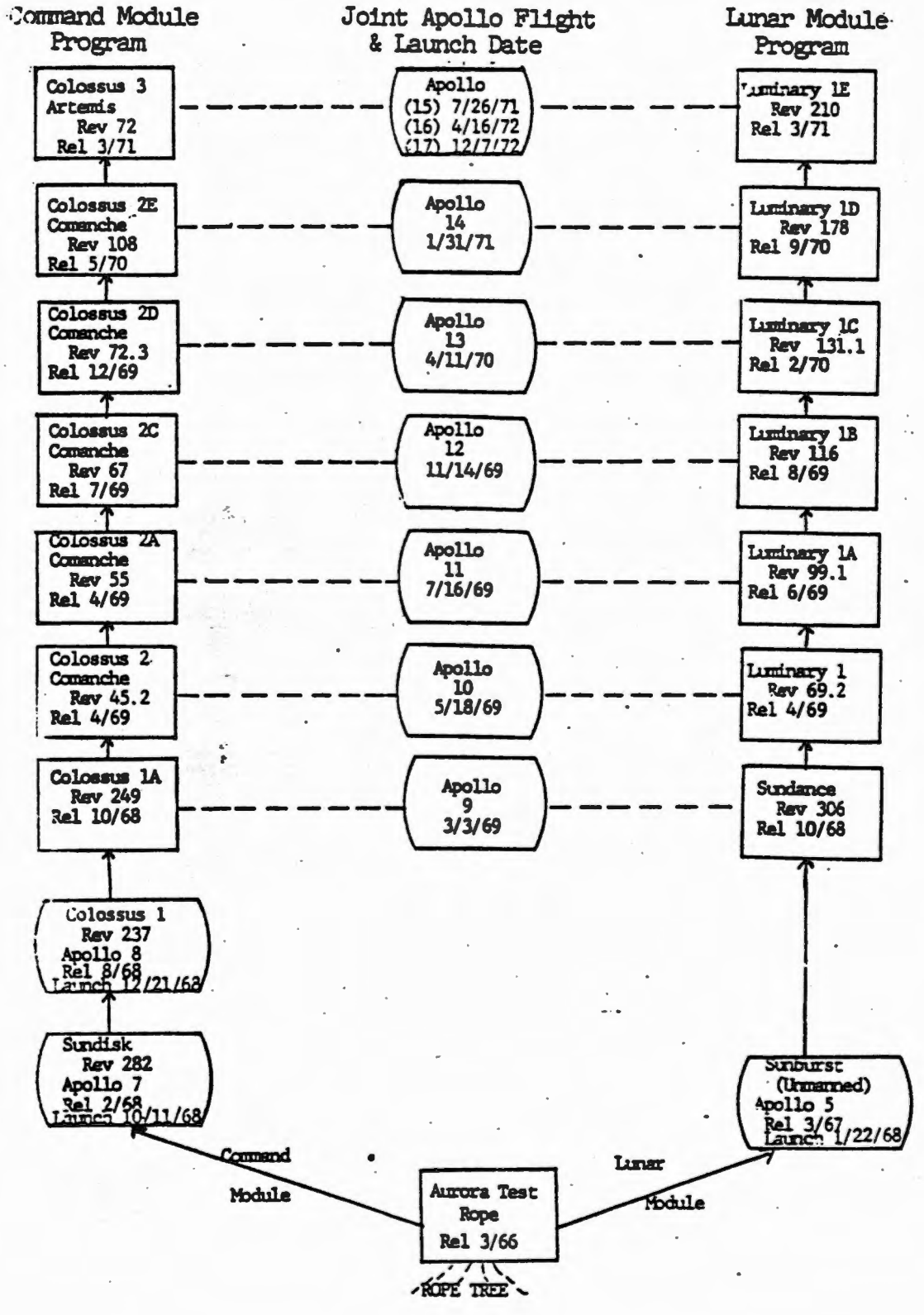
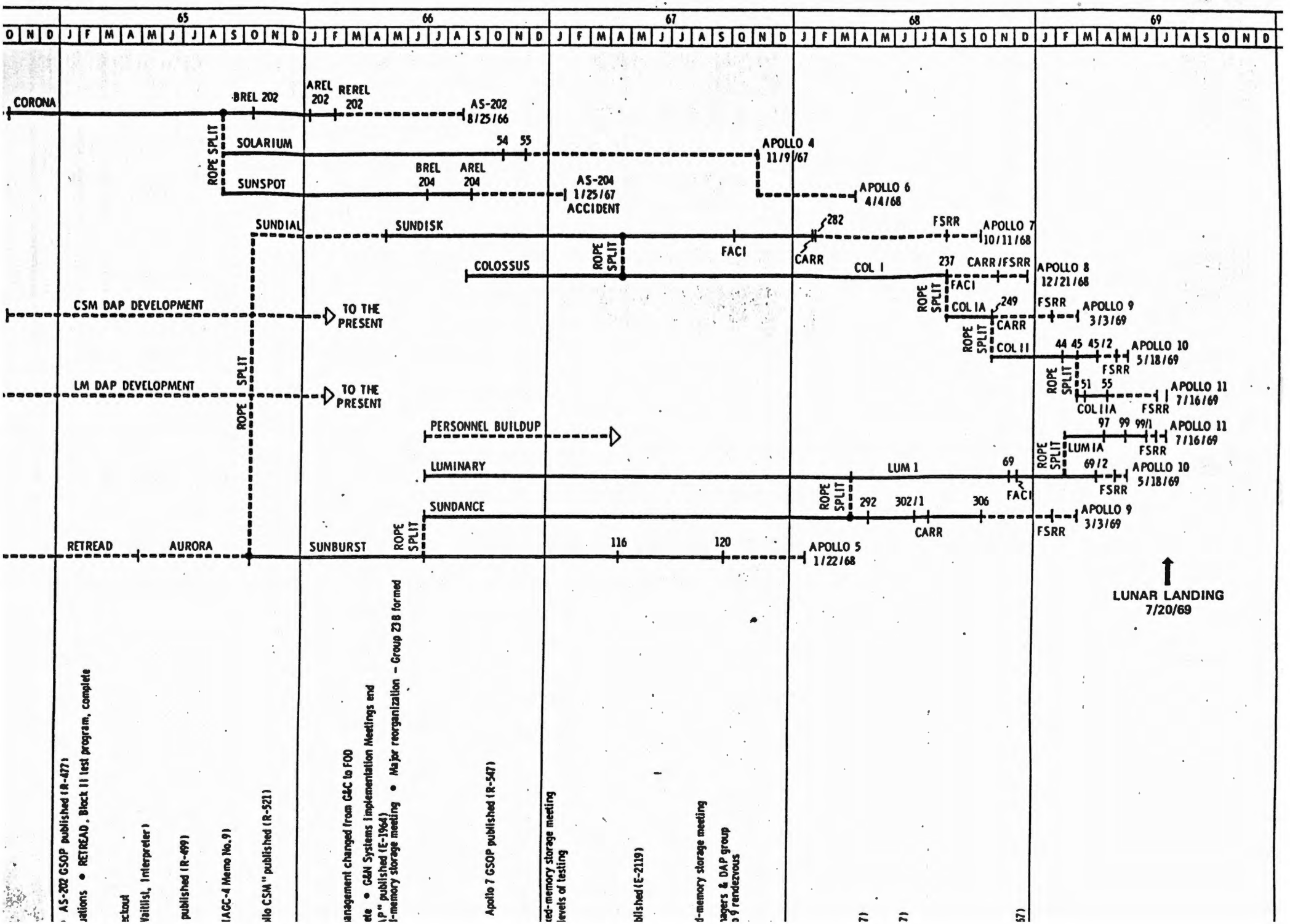


Figure 3-1 SOFTWARE RELEASES

Flight	Flight Program Name	Description	Launch Date	Crew
AS-202	CORONA	Suborbital; supercircular entry with high heat load	8-25-66	unmanned
Apollo 4	SOLARIUM	High apogee; suborbital; supercircular entry at lunar return velocity	11-9-67	unmanned
Apollo 5	SUNBURST	First Lunar Module flight; earth orbital	1-22-68	unmanned
Apollo 6	SOLARIUM	High apogee; suborbital; supercircular entry at lunar return velocity; verification of closed-loop emergency detection system	3-4-68	unmanned
Apollo 7	SUNDISK	First manned Apollo flight; earth orbital	10-11-68	Schirra Eisele Cunningham
Apollo 8	COLOSSUS I	First manned lunar-orbital flight; first manned Saturn V launch	12-21-68	Borman Lovell Anders
Apollo 9	COLOSSUS IA SUNDANCE	First manned Lunar Module flight; exercise of lunar landing, ascent and rendezvous techniques in earth orbit; EVA (Extra Vehicular Activity)	3-3-69	McDivitt Scott Schweikart
Apollo 10	COLOSSUS II LUMINARY I	First lunar-orbit rendezvous; Lunar descent to 50,000 ft	5-18-69	Stafford Young Cernan
Apollo 11	COLOSSUS IIA LUMINARY IA	First lunar landing (7-20-69)	7-16-69	Armstrong Aldrin Collins

Figure 1.2-2 The Apollo Flights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66
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CORONA
BREL 202
AREL 202
REREL 202
AS-202 8/25/66
ROPE SPLIT
SOLARIUM
54 55
APOLLO 4 11/9/67
SUNSPOT
BREL 204
AREL 204
AS-204 1/25/67 ACCIDENT
APOLLO 6 4/4/68
SUNDIAL
SUNDISK
282
FSRR
APOLLO 7 10/11/68
CARR
ROPE SPLIT
FACI
COLOSSUS
COL I
237
CARR/FSRR
APOLLO 8 12/21/68
CSM DAP DEVELOPMENT
TO THE PRESENT
ROPE SPLIT
FACI
COL IA
249
FSRR
APOLLO 9 3/3/69
CARR
ROPE SPLIT
COL II
44 45 45/2
APOLLO 10 5/18/69
FSRR
LM DAP DEVELOPMENT
TO THE PRESENT
ROPE SPLIT
ROPE SPLIT
51 55
APOLLO 11 7/16/69
COL IIA
FSRR
PERSONNEL BUILDUP
97 99 99/1
APOLLO 11 7/16/69
ROPE SPLIT
LUM IA
FSRR
LUMINARY
LUM 1
69
69/2
APOLLO 10 5/18/69
FSRR
ROPE SPLIT
FACI
SUNDANCE
292
302/1
306
APOLLO 9 3/3/69
CARR
FSRR
RETREAD
AURORA
SUNBURST
ROPE SPLIT
116
120
APOLLO 5 1/22/68
LUNAR LANDING 7/20/69

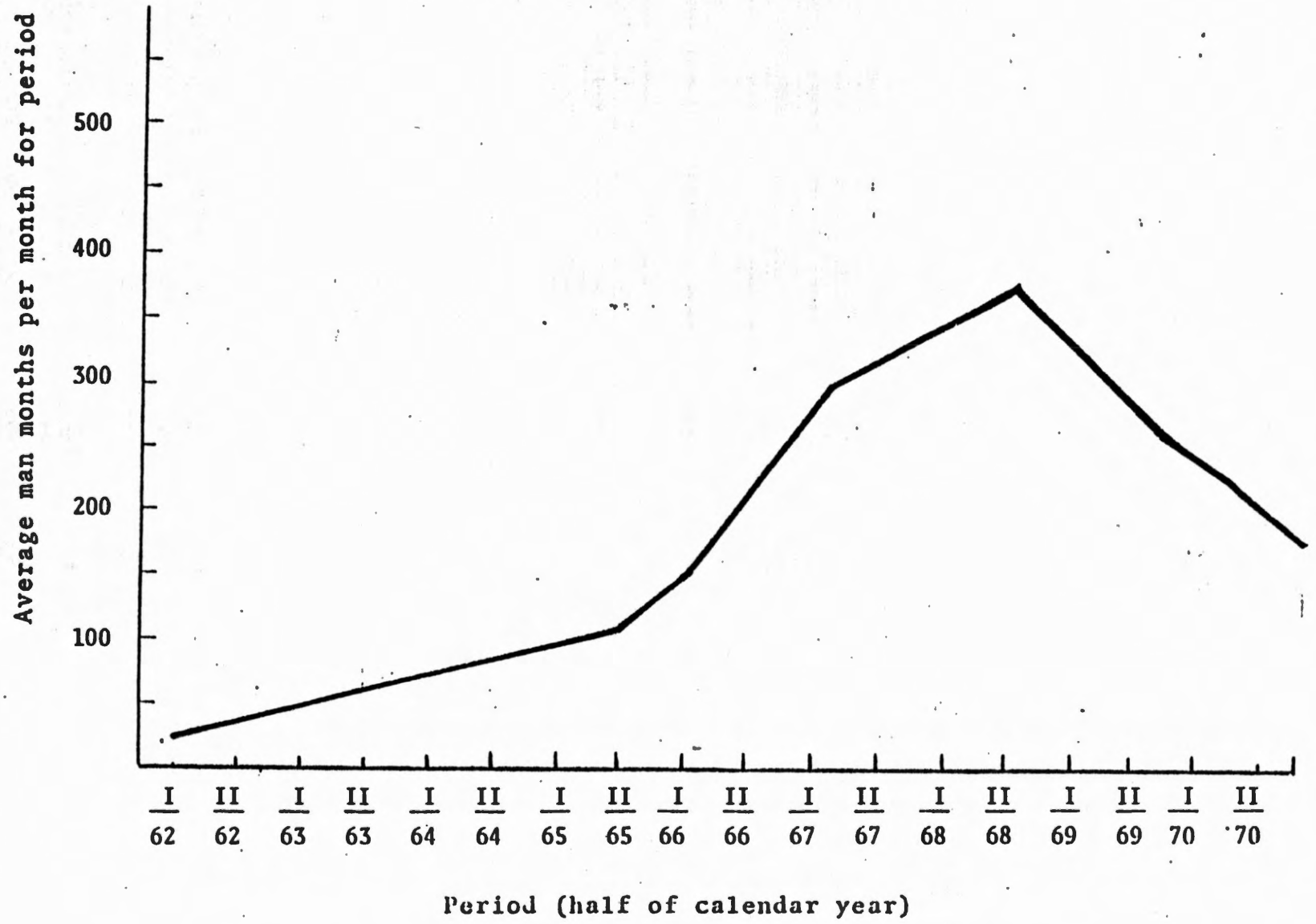

Figure 2-4 MANPOWER USAGE BY MIT/IL SOFTWARE EFFORT

Costs (1968 Dollars)

Coding $49/new word

Testing $13.5/flight word

RESULTS - THE TRACK RECORD

Table 4-1 REVISION IDENTIFIERS, FLIGHT PROGRAMS, SIZES, FLIGHTS

Prog Code	Revi-sions	Program Name	Flight Program	Total Words	New Words	Space Vehicle	Apollo Flight
D	1-282	Sundisk	Sundisk	36480	23100	C	7
C	1-237	Colossus	Colossus 1	37757	11770	C	8
C	238-249	Colossus	Colossus 1A	37854	110	C	9
M	1- 45	Comanche	Colossus 2	38575	2035	C	10
M	46- 55	Comanche	Colossus 2A	38610	110	C	11
M	56- 67	Comanche	Colossus 2C	38702	215 !	C	12
M	68- 72	Comanche	Colossus 2D	38702	34 !	C	13
M	73-108	Comanche	Colossus 2E	38402	1692 !	C	14
A	1- 72	Artemis	Colossus 3	38485 *	770 #	C	15
S	1-306	Sundance	Sundance	36424	28600	L	9
L	1- 69	Luminary	Luminary 1	37904	10560	L	10
L	70- 99	Luminary	Luminary 1A	38646	2310	L	11
L	100-116	Luminary	Luminary 1B	38502	700 !	L	12
L	117-131	Luminary	Luminary 1C	38502	150 !	L	13
L	132-178	Luminary	Luminary 1D	38202	940 !	L	14
L	179-210	Luminary	Luminary 1E	38452 +	770 #	L	15

610499 83866

Legend for column headed "Space Vehicle":

"C" means Command Module
"L" means Lunar Module

Legend for the columns headed "Total Words" and "New Words":

* Number taken from the program listing for Artemis 72
\+ Number estimated by experienced assembly contol supervisor
! Number taken from Rankin's thesis
\# Number estimated by averaging the numbers for the previous 4 flights

TOTAL NUMBER OF WORDS IN 16 RELEASES ≈ 611,000

TOTAL NUMBER OF WORDS CHANGED ≈ 84,000

KNOWN ANOMALIES IN FLIGHT PROGRAMS AT LIFT/OFF

FLIGHT	COMMAND MODULE	LUNAR MODULE
7	32	-
8	60	-
9	28	10
10	10	49
11	9	28
12	9	13
13	8	9
14	13	12
15	12	11
	181	132
	TOTAL 313	

No software anomalies revealed during Apollo flights - AS-202 thru

Apollo Soyuz