CR-128738

CR 72-588-001 L

Final Report for Laser Altimeter

NASA CONTRACT NUMBER NAS 9 - 10600
EXHIBIT A, PARAGRAPH 5.X
TYPE II

Prepared for
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

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RCA | Government & Commercial Systems
Aerospace Systems Division | Burlington, Massachusetts

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

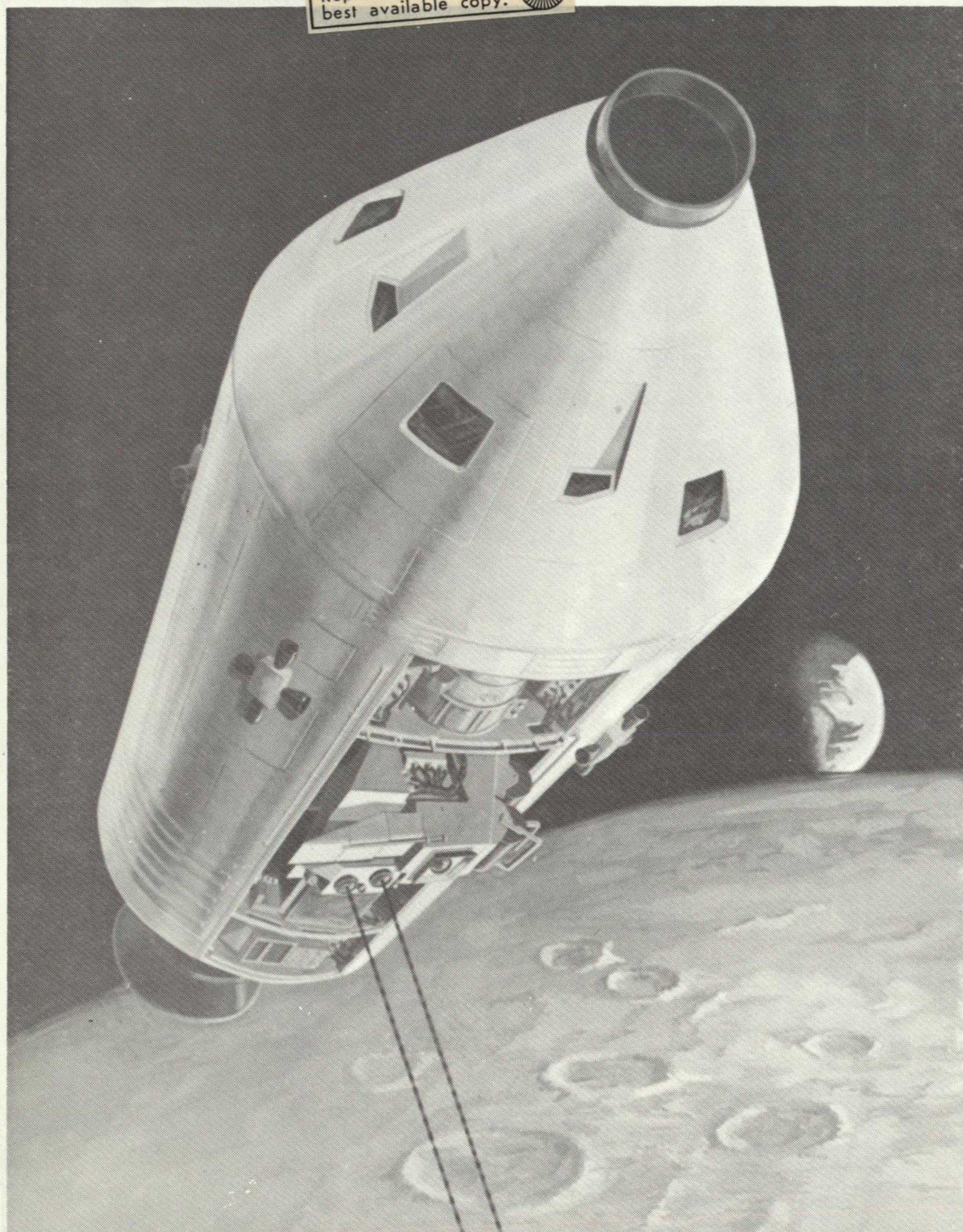
TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

LIST OF ILLUSTRATIONS

LIST OF TABLES



SECTION 1
GENERAL

The decision to procure Laser Altimeters for inclusion in the Apollo Lunar Orbital Experiments missions was implemented by the NASA MSC award of Contract NAS 9-10600 to the RCA Aerospace Systems Division with an effective start date of 12 January 1970. The final report summarizes the ensuing contractual effort from inception through completion of Flight Hardware delivery.

1.1 PURPOSE OF PROGRAM

The Laser Altimeter program was established to provide flightworthy equipment for precisely measuring the altitude of an Apollo vehicle above the lunar surface from an orbit of 40 to 80 nautical miles. Further, the program provided for interface and integration support and a test regimen to assure that properly qualified hardware was available and installed to support Apollo flight schedules. Table 1-1 outlines the technical characteristics of the altimeter developed for this purpose.

1.2 DEFINING DOCUMENTS

1.2.1 Contractual

Contract NAS 9-10600 and supplemental agreements thereto constituted the defining instrument. Principal sections were the Contract Schedule, Articles and Referenced Procurement Regulations; Contract Exhibit A - Statement of Work, and Exhibit B - Technical Specification for Laser Altimeter. A number of subsidiary documents were invoked by the contract; including North American Rockwell Performance and Interface Specification, SD 69-135.

Table 1-1. Laser Altimeter Characteristics

Operating Altitude

Nominal 60 nautical miles (111 Km)

Maximum 80 N. Mi.

Minimum 40 N. Mi.

Altitude Resolution - 1 Meter

Altitude Accuracy - ± 2 Meters

Field of View - 200 Microradians

Modes of Operation

Automatic - 3/Minute

Camera - <3.75/Min.

Transmitter

Output - 250 Millijoules, nominal, per pulse

Beamspread - 300 Microradians
80% Included Energy

Output Word - Normal-Binary-Serial (18 bits), altitude in meters plus 6 binary status bits to SDS
18 bits, altitude to Mapping Camera

Analog - 6 Status Signals

Inputs

From Mapping Camera - Pre-trigger-Discrete
Data Request-Discrete

From Spacecraft -
Power - 28 VDC <50W. Ave.
400 Hz 3 Ø <7 VA/Ø

Weight - 50 lbs.

Volume - 1.5 ft.^{3}

Cooling - Passive

1.2.2 Negotiated Interfaces

Several tri-partite Interface Control Documents were negotiated at various Interface Working Group meeting, involving NASA-MSC, North American Rockwell (Space Division) or Fairchild Camera and Instrument Co. (Space and Defense Systems) and RCA Corporation; (Government and Commercial Systems, Aerospace Systems Division.) Contractual responsibility for preparation and issuance of these documents, listed below, was given to N/R and FSDS.

MH 01-12622-234	CSM/Laser Altimeter Electrical Requirements	(N/R)
MH 01-12623-434	CSM/Laser Altimeter Functional Requirements	(N/R)
MH 01-12625-434	CSM/Laser Altimeter Ground Requirements	(N/R)

MH 01-12914-234	Laser Altimeter, BTE/Apollo GSE Interface Requirements	(N/R)
1231-JC-1	LA/MC Electrical Interfaces	(FSDS)
1231-JC-2	LA/MC Envelope	(FSDS)
1231-JC-3	LA/MC Installation	(FSDS)
1231-JC-4	LA/MC Environmental Requirements	(FSDS)

1.2.3 Documents Developed on Contract

Principal documents developed under the contract were of three types: procedural, control and technical definition.

1.2.3.1 Procedural Documents

This category included Program Management Plan, Reliability and Safety Plan, and Quality Program Plan. These documents were prepared by RCA, negotiated in detail with MSC, submitted to and accepted by MSC.

1.2.3.2 Control Documents

Control documents included monthly forecasts and reports to MSC of financial status, technical and manufacturing progress and of documentation submissions. Internal control documents included work breakdown structures, task directives, manpower plans and schedules, detailed and summary PERT networks, material flow and accumulation lists and subassembly line-of-balance for flight hardware.

1.2.3.3 Technical Definition Documents

Technical definition documents comprised end item specifications, manufacturing drawings and specifications, test specifications, and test procedures, as developed and submitted by RCA and listed below.

(1) Specifications

2364402	Contract End Item Specification, Laser Altimeter
2364148	Contract End Item Specification, Laser Altimeter GSE
2364489	Certification Test Specification; Laser Altimeter
2352532	Acceptance Test Specification, Laser Altimeter
2352648	Qualification Test Specification, Laser Altimeter
23639	Acceptance Test Specification, Laser Altimeter GSE

(2) Drawing Sets

Manufacturing drawings and specifications developed for the Laser Altimeter and GSE stem from the following top assembly drawings and parts lists:

2364000	Laser Altimeter Assembly	Group 501 Prototype LA
		Group 502 Flight LA
2363906	Laser Altimeter GSE Assembly	

(3) Test Procedures

The test procedures prepared by RCA for acceptance and qualification of the Laser Altimeter and GSE included the following:

CR 70-588-14H	LA-ATP-A(7) Acceptance Test Procedure for Laser Altimeter
CR 70-588-14H1	GSE ATP-A(2) Acceptance Test Procedure for Laser Altimeter Ground Support Equipment
CR 70-588-14U	Qualification Test Procedure for Laser Altimeter
CR 71-588-006E	EMI Qualification Test Procedure for Laser Altimeter

1.2.3.4 Test and Analysis Reports

Test and analysis reports included the following:

(1) Acceptance Test Reports were prepared for each completed test of each Laser Altimeter and for each set of GSE

(2) A Qualification Test Report consisting of a summary volume and fourteen appendices was submitted at completion of qualification testing

(3) A Design Verification Analysis report was submitted with the Qualification Test Report in response to certification requirements

(4) The Thermal Analytical Model (TAM) of the LA was submitted, revised based on updated interface inputs, then completely revised and reissued as the result of J mission redefinition and RCS Plume protective door additions to the SIM.

1.2.4 Extra-contractual Documents

Two documents not formally invoked by contract, but which became guidelines were Configuration Management Requirements for Apollo Lunar Orbit Experiments, No. MSC-02436 Rev. A and Apollo CSM Lunar Experiment Hardware Environmental and Certification Requirements Document (PD 13/M375).

1.3 CONTRACT DELIVERABLE HARDWARE

1.3.1 Original Contract Requirement

Deliverable hardware items under terms of the contract were:

One - Laser Altimeter Mass Mockup
One - Laser Altimeter High Fidelity Mockup
One - Laser Altimeter Prototype
One - Qualification Laser Altimeter (Same as Flight LA's)
Three - Flight Laser Altimeters
Two - Optional Flight Laser Altimeters.
Three Sets - Ground Support Equipment

1.3.2 Additional Deliverable Hardware

One Laser Altimeter Electrical Simulator was added to the program to support the N/R ATEE tests.

The option for the two flight LA's was exercised by MSC. Work was later stopped on one of these units as a consequence of the reduction in the number of Apollo flights.

1.4 TECHNICAL REQUIREMENT CHANGES

1.4.1 Laser Altimeter

The original technical specification allocated a large, rectangular volume to the LA and provided for an external optical coupler between the LA and Mapping Camera.

The negotiated contract specification provided for the LA to be hard mounted to the MC to preclude the necessity for external optical coupling and to assure precise LA/MC boresighting. As a consequence of the hardmounting to the MC, the LA vibration, pressure and thermal environmental requirements increased in severity.

1.4.2 Ground Support Equipment

The proposed GSE consisted of one unit. Post-contractual interface discussions established that access and handling on the pad would be extremely difficult with the proposed configuration. The GSE was therefore changed to a two-unit configuration with an extensible optical interface assembly.

1.4.3 Test

Changes in test philosophy and requirements related principally to qualification testing:

- o The EMI test, proposed as a development test on the LA prototype, was changed to a qualification test on the Qual LA.
- o The vibration test of the Qualification unit was increased in severity by the requirement to add a re-test capability test at 1.3 times the acceptance test level.
- o The low pressure solar energy qualification test was required to simulate at least 32 lunar orbits because of mission timeline changes.
- o Demonstration of the ability to withstand SIM door jettison and SLA separation shocks was added to the qualification requirements.

SECTION 2

SUMMARY OF CONTRACT RESULTS

2.1 HARDWARE DELIVERIES

Items were delivered on contract in accordance with the schedule below:

		Initial Acceptance Date	Destination
Laser Altimeters			
Prototype	(S/N 0001)	9 Oct. '70	WSMR
Flight Unit No. 1	(S/N 0003)	27 Jan. '71	FSDS
Flight Unit No. 2	(S/N 0004)	24 Mar. '71	FSDS
Flight Unit No. 3	(S/N 0005)	6 May '71	FSDS
Flight Unit No. 4	(S/N 0006)	7 Sept. '72	KSC
Qualification Unit	(S/N 0002)	11 Feb. '71	In Place
Mock-ups			
Mass Mock-up		15 June '70	In Place
High Fidelity Mock-up		1 Sept. '70	MSC
Electrical Simulator		23 June '70	N/R
Ground Support Equipment			
S/N 001		9 Oct. '70	In Place
S/N 002		18 Nov. '70	FSDS
S/N 003		30 Nov. '70	KSC

The Prototype unit was shipped:

(1) To FSDS to prove LA/MC integration capability and techniques;

(2) To WSMR to test distance measuring capability over an extended range;

(3) To MSC for 2TV2 test;

(4) To N/R-Downey for SIM/SLA shock tests;

(5) To N/R-Downey for pre-Apollo 17 ATEE tests.

After each test the prototype was returned to RCA, then refurbished, tested and inspected to the extent required for its next use.

Flight Unit No. 1 was returned from KSC via FSDS for minor modification as a result of problems encountered in Qualification Testing and was reshipped to FSDS on 6 July 1971.

The Electrical Simulator was returned to RCA after ATEE testing. It was later modified and shipped for GSE Validation at KSC.

Retrofits were undertaken on flight units after Apollo 15 and Apollo 16. Flight units were re-submitted for acceptance after retrofit and complete acceptance retesting.

Flight Unit No. 2, LA S/N 0004 was on the Apollo 15 vehicle. Flight Unit No. 3, LA S/N 0005 was on Apollo 16. Flight Unit No. 4, LA S/N 0006 was on Apollo 17, with No. 1, LA S/N 0003 as backup not flown.

2.2 TEST RESULTS

Most significant of the tests conducted on the LA were the ranging tests at White Sands Missile Range and the Qualification Test. The WSMR tests demonstrated the ability of the Altimeter to measure range under signal conditions similar to those expected in lunar orbit. The atmospheric attenuation during these tests offset the decreased range (27 vs. 60 nautical miles). Performance in lunar orbit extrapolated from these test results exceeded the calculated worst case requirements.

The Qualification test exposed the LA to a sequence of environments generally more severe than expected in the Apollo missions. Minor problems encountered in vibration testing were corrected in all flight units so that the Altimeters were qualified for flight.

Acceptance tests of each unit included vibration and thermal-vacuum exposure and complete performance verification. The test series was established to give assurance that the units had been so manufactured as to perform in accordance with the design requirements.

Flight data analysis after Apollo 15 and Apollo 16 indicated the desirability of hardware changes and of increased TV exposure in acceptance testing. Flight and Qual LA's remaining after each flight were retrofitted and re-tested in accordance with procedures revised to reflect hardware and test requirement changes.

2.3 FLIGHT EXPERIENCE

In accordance with NASA J series mission plans, Laser Altimeters were installed in the Apollo 15, 16, and 17 spacecraft. Flight experience to the time of report preparation is summarized below.

2.3.1 Apollo 15 Mission

The LA operated as planned through revolution 24 of lunar orbit.[1] During the first operating period of about 11 hours (rev. 3 through 9) the orbit was not circularized; therefore, the altitude was below the 40 nautical mile minimum range gate of the LA for about half the time. Whenever the altitude was within the design range, valid altitude data was obtained. Later in the mission the laser output degraded, resulting in some loss of altitude data. A subsequent anomaly attributed to the breakdown of a high voltage vacuum relay prevented obtaining further altitude data. Sufficient data was obtained so that all of the primary mission objectives were achieved.

Analysis of the Apollo 15 anomalies resulted in changes to LA's for subsequent flights. Removal of the high voltage relay, changes in laser module processing, and addition of a servo loop to compensate for a possible gradual decrease in laser efficiency were accomplished for Apollo 16.

2.3.2 Apollo 16 Mission

The Laser Altimeter was operated for seven periods in accordance with the flight plan, as revised during the mission to accommodate the delayed LM landing. Valid altitude data was provided for two thirds of the "shots" during the mission. Sufficient data was obtained to accomplish the Apollo 16 mission mapping objectives. The results for each operating period are tabulated in Table 2-1.

Table 2-1. Apollo 16 Laser Altimeter Operation Summary

Operating Period No.	Lunar Orbital Revolution Nos.	Time-Hours	"Shots"	Percent Valid Altitude Data
1	3-4	3/4	120	100
2	16-17-18	3	430	74
3	28-29	3	455	63
4	37-38-39	4	553	68
5	46-47	2 1/4	359	69
6	59-60	2	341	56
7	63	1	148	22
	Mission Totals	16 Hours	2406 Shots	66% Valid Data Points

One of the changes implemented for Apollo 16 was a control circuit which operated to increase laser input by one step if the output of the previous shot was below a pre-set threshold value. Conversely, if the previous output exceeded the threshold the input was decreased by one step. Five such steps were available in addition to the initial input value (Step 0). When the laser output degraded sufficiently to require compensation, the operation was such that alternate shots would be above and below the threshold, i.e., Step 0, Step 1, Step 0, Step 1 - - -.

In the Apollo 16 mission the combination of large steps (as compared to the threshold) and unexpectedly rapid decrease in efficiency, resulted in output on the lower step insufficient to give altitude data under all conditions; however, the compensation operated to insure that an adequate quantity of altitude data was obtained. After the compensation servo started operating, the altimeter gave valid altitude data on alternate shots on the sunlit side of the moon and on nearly every shot on the dark side. This operating condition started during the second operating period, after the first Step 1 was required, and continued until the last half hour of the last operating period when the laser efficiency had decreased to the extent that Step 5 was continuously required.

Partial data from the last two operating periods indicates that the receiver sensitivity was abnormally reduced during light side operation. This phenomenon contributed to loss of data during these last two periods.

As a result of the Apollo 16 flight experience, the laser module Q-switch bearings were changed to a type with the only lubricant vacuum impregnated into the ball retainer. (Lubricant contamination of optical elements was a suspected cause of laser output degradation.) Flash lamp envelope material was changed to a higher purity grade of fused quartz (Suprasil) to eliminate loss of output due to solarization. The control servo was changed to provide, in effect, nine steps of 35 volts, as opposed to the five 70-90 volt steps of the Apollo 16 unit. These changes were incorporated in the Apollo 17 flight and backup units.

2.3.3 Apollo 17 Mission

The number of operations of the LA during the Apollo 17 mission exceeded 4000, although only 2400 had been scheduled in the flight plan. Valid data yield for the 4000 operations exceeded 99 percent. Results, based on data available at time of writing, are tabulated in Table 2-2.

Ten and one half hours of operation of the LA independent of the MC were added during a CMP sleep period, revolutions 67 to 72, thus providing an additional 1800 data points. On two occasions the SC rolled out of the "SIM Bay" attitude. Each time the LA measured the slant

Table 2-2. Apollo 17 Laser Altimeter Operation Summary

Operation Period	Rev. No.	G.E.T. (Plan or Actual)		No. of Operations In Period	Cum. Total Opns.	Percent Valid Data	Cum. Percent Valid Data
1	1-2	90:48	91:29	72	72	100	100
2	13-14	113:59	115:05	156	228	98+	99
3	15	116:03	117:27	201	429	100	99+
4	24	133:47	134:54	141	570	100	99+
5	27-29	140:50	144:48	486	1056	100-	99+
6	38	161:38	163:34	280	1336	100-	99+
7	49	183:20	184:27	165	1501	98	99+
8	62	209:04	211-10	199	1700	98	99+
9	65-66	216:15	218:09	260	1960	99	99+
*10	67-72	219:59	230:21	1866	3826	98+	99
11	73-74	232:37	234:09	200	4026	99+	99

*This operating period was not included in pre-mission flight plan.

range until it exceeded the 80 nautical mile range gate limit of the LA, in spite of an unfavorable angle of incidence at the lunar surface. The LA was also operated at three occasions while retracted into the SIM Bay, with no adverse effects.

The PFN controller operated occasionally to increase the laser input. Although on two occasions step 3 of the controller was activated, generally operation was in step 0. Early in the last period of operation the controller was stepping in steps 0, 1, and 2. At the end of the period operation was predominantly in step 0 with an occasional step 1. It was apparent from performance and other telemetry data that the decrease in laser efficiency during the mission was quite small.

In summary, there were no anomalies, the number of operations was increased by two-thirds during the mission, and data validity approached 100 percent for the entire mission. Operation was entirely successful and mission objectives were surpassed.

2.4 COMPARISON OF MISSION PERFORMANCE

The performance achieved in the three missions is compared in the table below.

		Apollo 15	Apollo 16	Apollo 17
Hours of operation (Approx)	Planned Actual	35 30	17 17	17 27
Number of shots (Approx)	Planned Actual	5000 4200	2400 2400	2400 4000
Portion of mission in which valid data was obtained		First half only	All but last half hour	Entire mission
Percentage of valid data during operation		79% First Half 0% Second Half	65%	99%
Mission primary objectives achieved		Yes	Yes	Yes

SECTION 3

MANAGEMENT HIGHLIGHTS

A number of factors combined to make the management of the Laser Altimeter program a challenging task. The abbreviated time scale for hardware development was aggravated by conceptual and form factor changes at contract outset and by the fact that interfaces with the spacecraft and the Mapping Camera were then incompletely defined. Although the experiments were not man-rated, flight critical hardware, the Apollo requirements and procedures were generally invoked. In fact, the control documentation required for the Laser Altimeter program exceeded in some respects that for the Lunar Module Program.

The definition of interfaces required the agreement of three parties with a fourth party as an observer and adviser. The LA interfaces were documented either by North American Rockwell or by Fairchild Space & Defense Systems Division. Interface meetings and agreements were reached with N/R, RCA and MSC as signatories and with FSDS observing or with FSDS, RCA and MSC as signatories and with N/R observing.

Later in the program, hardware, test equipment, data and personnel was supplied to support testing at N/R; testing at MSC; integration and testing at FSDS; integration, testing, and checkout at KSC; and flight support at MSC.

3.1 ORGANIZATION

The LA Program organization was a functional one. The program manager, reporting through one level of management to the RCA Divisional Vice President and General Manager was empowered to give direction to the various functional groups. For a portion of the program a deputy program manager was assigned, acting principally in the areas of schedule control and documentation. The program manager also acted as technical director and interface negotiator.

A Contract Administrator was assigned to the program, administered the contract and participated in all negotiations from inception to completion.

A Financial Administrator was assigned to the program for its total duration, working in the program office.

Responsibilities were assigned in other functional groups as listed below. Each of these individuals had as his prime responsibility the coordination and direction of the function being represented:

- Reliability & Safety Engineer
- Quality Assurance Engineer
- Data Manager
- Manufacturing Coordinator
- Engineering Project Leader
- Electrical Design Leader
- Drafting Leader

Each reported administratively to his functional line manager and received project direction from the LA program office.

3.2 PROCEDURES AND INTERNAL CONTROL DOCUMENTS

RCA standard procedures and documents were used where applicable. Other document formats developed for the LM program or by MSC or DOD augmented the RCA documents to fulfill special LA program requirements.

A work breakdown structure was developed for the program and formed the basis for task assignment, schedule, and cost control. An overall program PERT network and networks for each of the deliverable hardware items were maintained for schedule control and reporting.

During the engineering release and first unit manufacturing phase these were particularly useful. Line of balance for subassemblies and final assemblies was maintained by manufacturing and reviewed at the weekly program reviews.

3.3 MEETINGS

A large number and variety of meetings was held during the program which involved MSC and RCA representatives. These included but were not necessarily limited to the following:

- Contract Specification Negotiation
- Contract Cost Negotiation
- Interface Meetings - N/R, MSC, RCA
- Interface Meetings - FSDS, MSC, RCA
- Preliminary Design Review
- Critical Design Review
- Monthly Program Reviews
- KSC Indoctrination Meetings
- Change Negotiation Meetings
- Configuration Management Definition Meeting
- Acceptance Readiness Reviews
- Flight Readiness Reviews
- ECP Presentation Meetings
- Technical Review Meetings
- Flight Support Indoctrination
- Plume Shield PDR and CDR

RCA also conducted monthly program reviews with the Divisional Vice President and General Manager. In addition, during critical periods weekly meetings were held preceding the normal work day. An MSC RASPO representative generally attended these meetings. Daily coordination meetings with design engineering, manufacturing, quality assurance, engineering design support, and the PMO provided fast response for real time problem solving and direction.

3.4 SUBCONTRACT

There was only one major subcontract for design and manufacture of hardware, that for the telescope assembly. The design to meet the optical and environmental requirements was a challenging one. The implementation resulted in a difficult precision assembly of reflective and refractive optical elements in a sealed, essentially non-repairable assembly.

Technical control by RCA included preparation and negotiation of the telescope specifications with the subcontractor, periodic reviews of the subcontractor design, participation in and assistance to the subcontractor in thermal and dynamic stress analysis and design. Test procedures and testing were reviewed and approved by RCA at all stages.

Schedule and cost control problems required that RCA direct the subcontractor in preparation and maintenance of appropriate documentation.

During the design phase, RCA optical and mechanical engineers met with the subcontractor almost daily. During the manufacturing and test phase of the subcontract, the RCA subcontract administrator held daily meetings with the subcontractor. Several meetings were held with MSC representatives, the subcontractor's top management, and the RCA program manager to assess status and progress and to assure that the telescopes did not impact the Apollo experiment schedule.

Three of the flight telescopes produced met all of the specification requirements and were incorporated in the LA's for Apollo 15, 16, and 17. The fourth flight telescope developed an anomaly after pressure testing which eventually rendered it unacceptable for flight. The qualification unit telescope which had a minor deviation was therefore used in the Apollo 17 backup LA.

The design and manufacture of the telescopes with their severe environmental and optical requirements represented a high level of technical achievement.

SECTION 4

TECHNICAL

The original RCA proposal for the Laser Altimeter was for a regular, rectangular unit to fit the space then considered available. At the time of negotiation of the LA specs, the configuration and interfaces changed. As a result, the actual LA packaging and mechanical implementation differed markedly from that proposed. The basic electrical and laser design closely followed the proposal, however. The optical design of the telescope changed from refractive to largely reflective (catadioptric) to accommodate the environment which became established through interface meetings. The proposed four-inch diameter apertures were retained, however. Interface constraints which changed during the design phase also had major impact upon the structural and thermal design of the LA.

Access and space constraints on the pad at KSC caused the proposed single-unit GSE to be separated into an electronics unit which could be 45 feet from the installed LA, and an RT unit at the installed position to interface with the LA.

The Laser Altimeter and associated Ground Support Equipment as developed for the program are described in this section.

4.1 SUMMARY DESCRIPTION

The Laser Altimeter, shown in Figures 4-1, 4-2, and 4-3, is an irregularly shaped structure, formed from a basic aluminum casting and aluminum sheet surfaces to fit the available space. The external surfaces carry three connectors, the transmitting and receiving telescope apertures, a checkout and alignment telescope (CAT) window port, a beam splitter keyhole for changing the position of the internal optics, an events counter, telescope exhaust and pressurizing ports, and three interface mounting points.

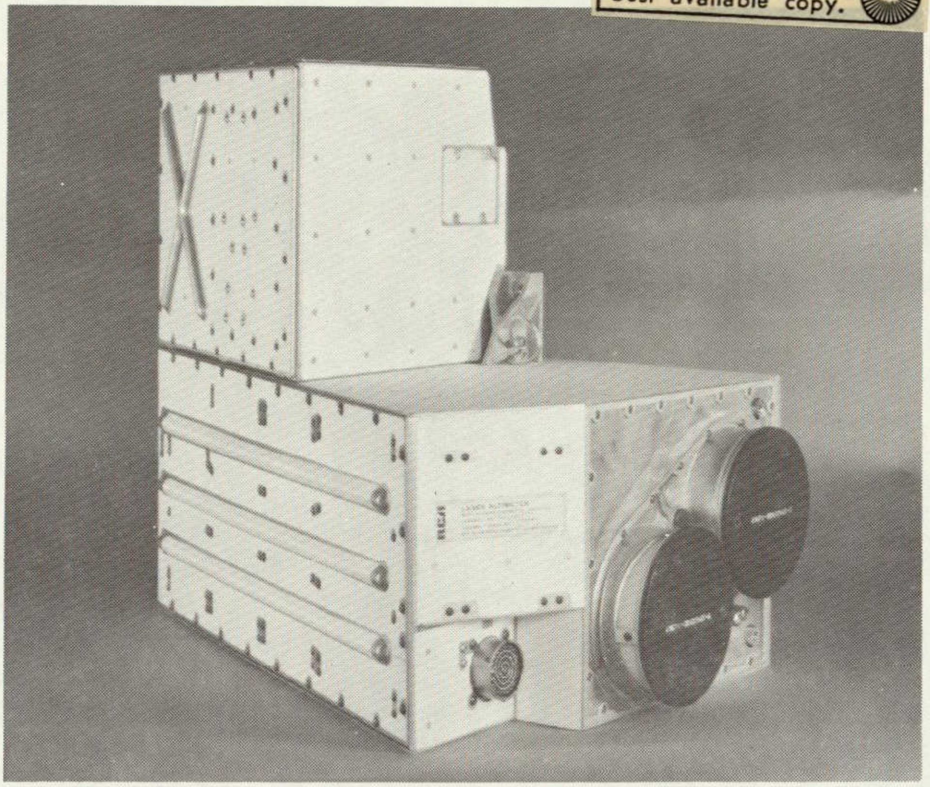


Figure 4-1. Laser Altimeter - Left Oblique View

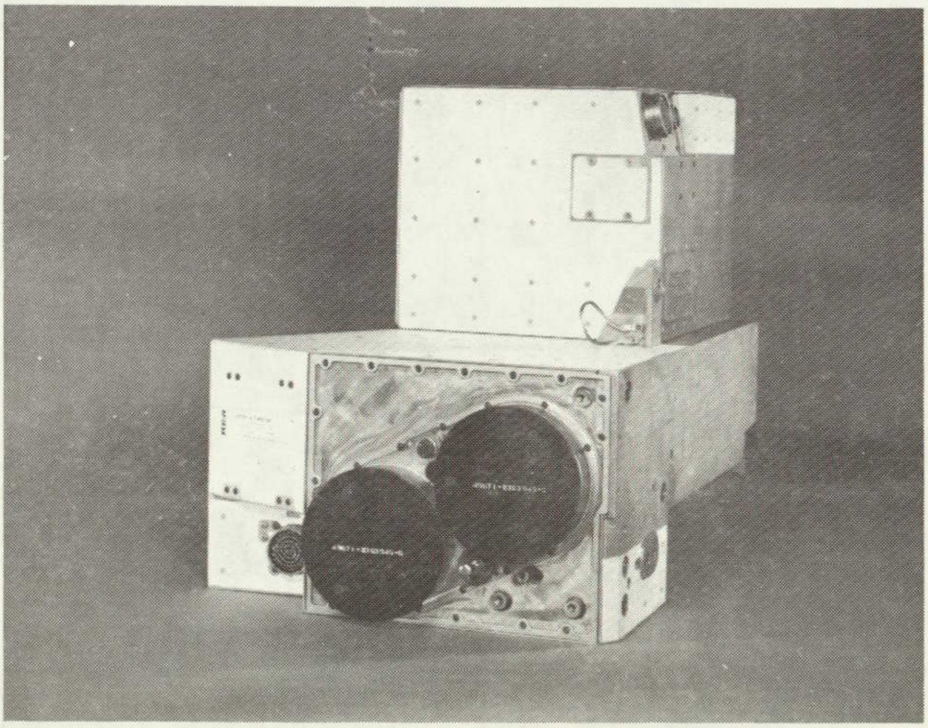


Figure 4-2. Laser Altimeter - Right Oblique View

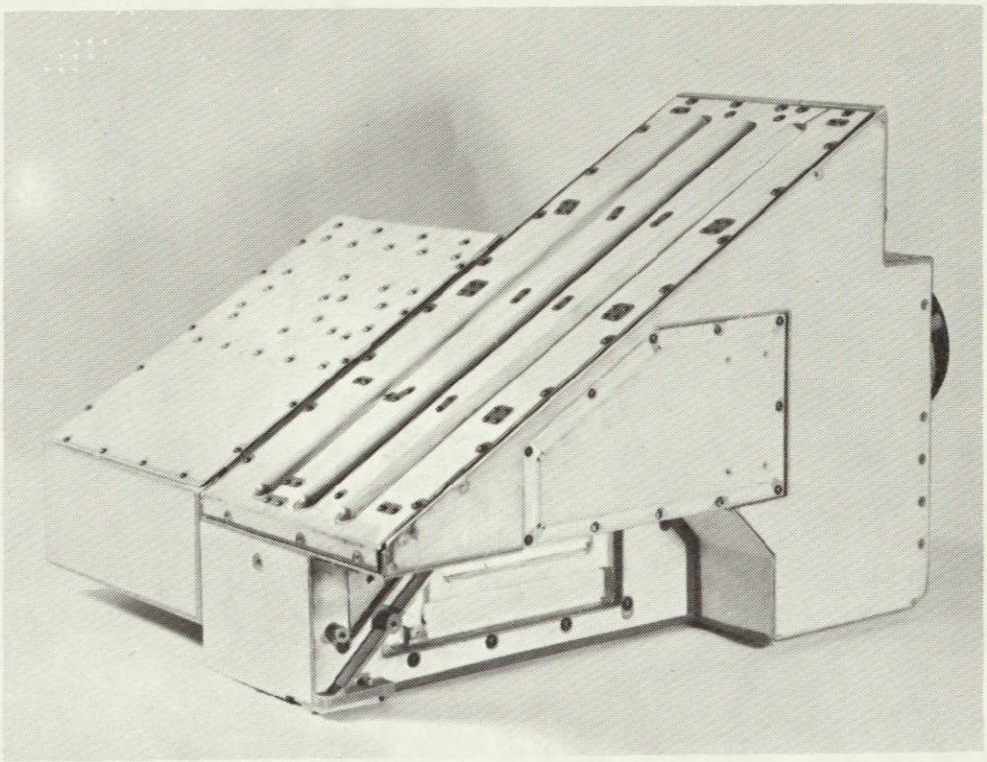


Figure 4-3. Laser Altimeter - Bottom View

The ruby laser and associated optics transmit an intense light (laser) pulse of narrow beamwidth and short duration to the lunar surface. A portion of this light pulse is reflected from the lunar surface and is received by the receiving telescope. The received light pulse is detected by the photomultiplier tube and is then processed by the LA which converts the time difference between the transmitted and the received pulses into range information with a resolution of one meter. The altitude data, in natural binary, serial format, is delivered to the mapping camera (MC) for recording on film and to the Scientific Data System for telemetry to earth.

The LA has two modes of operation, Camera and Automatic. In the automatic mode, the LA automatically ranges once every 20 seconds. In the Camera Mode, the Mapping Camera (MC) commands the LA to range once every 16 to 34 seconds. In addition to altitude data, the LA also provides digital and analog status signals for telemetry.

4.2 DESIGN ANALYSIS

The design characteristics of the LA were derived from the requirements of specified accuracy, resolution, probability of detection, operating altitudes, and characteristics of the operating environment which include the velocity of propagation of light, the lunar surface reflectivity, and the background (solar) radiation incident upon the lunar surface and upon the LA receiver optics.

These parameters are encompassed in the range equation. The solution of this equation was optimized to best fit the system design constraints.

The optics, laser, and mission parameters were defined based on the specifications and RCA's experience. The laser range equation was then used to calculate the reflected laser energy incident upon the photomultiplier tube (PMT) photocathode. This resulting received energy and the assumed characteristics of the receiver were used to calculate the probability of detection of the laser return and the average false alarm rate (FAR) and thus to verify the suitability of the design assumptions.

4.2.1 Energy Return E_R

The energy return on the PMT faceplate is given by:

$$E_R = E_T \cdot B \frac{\rho \cdot d R^2}{4 \cdot R^2} \cdot K_R$$

This equation assumes a flat Lambertian surface reflection, where a fraction of the energy, ρ, is reflected into a π steradians

B = Beamwidth factor relating receiver field-of-view (FOV) and transmitter bandwidth = 0.625

E_T = Laser energy transmitted in joules

$= E_L \times K_T \times K_{BW} = 128$ mj

where

E_L = is the total energy in the raw laser beam, or at least 200 millijoule, a design assumption.

K_T = is the transmitter optics transmission factor or 0.80 minimum a design requirement for the LA telescope.

K_{BW} = is the fraction of energy from the transmitter optics within a 0.3 milliradian beam. This factor is at least 0.80 as listed in Table 4-1.

T_T = 200 mj x 0.8 x 0.8 = 128 mj

Table 4-1. Transmitter Beam Characteristics of LA Flight Units (Measured)

Characteristic	S/N 0003 Update	S/N 0004 Apollo 15	S/N 0005 Apollo 16	S/N 0006 Apollo 17
Energy in 0.2 mr (%)	67	59	55	75
Energy in 0.3 mr (%)	95	86	83	87
Total Laser Energy (mj)	267	357	270	286
Energy in 0.2 mr (mj)	188	211	148	216
Energy in 0.3 mr (mj)	253	307	224	248

The receiver FOV of 0.2 mr is defined by the receiver telescope field stop. In Figure 4-4 the predicted energy in the transmitter laser beam is plotted against beam angle. Assuming perfect boresight, the 0.2 milliradian receiver FOV will intercept slightly more than fifty percent of the total energy or about five eighths of the energy in the 0.3 milliradian transmitter beam. Therefore, B = 0.625.

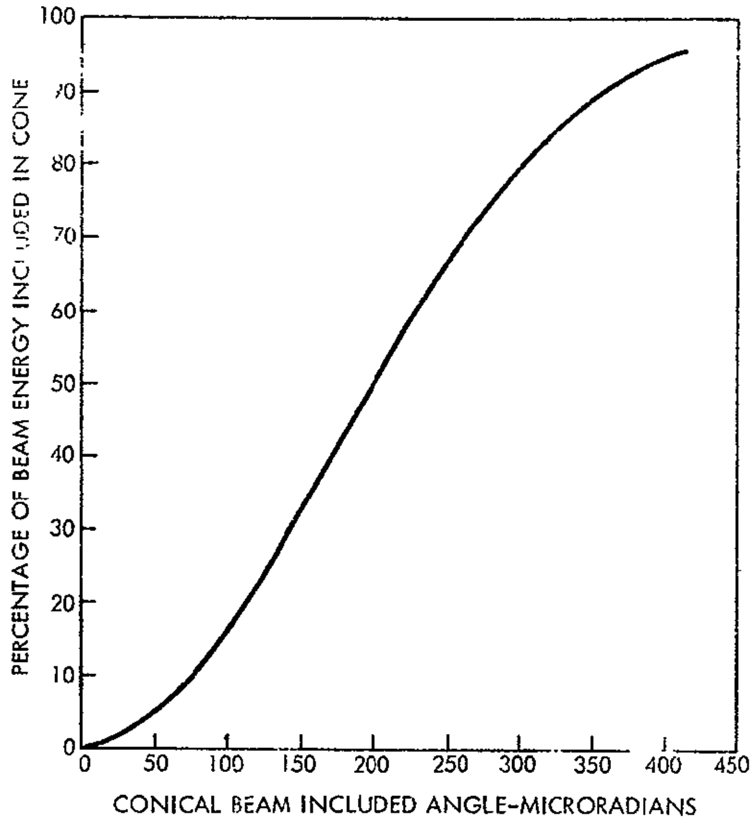


Figure 4-4. Laser Beam Energy Distribution

Table 4-1 lists the measured beam characteristics of the LA Flight transmitters.

ρ = lunar surface reflectivity minimum = 0.05. (lunar experiment reports indicate the reflectivity figure is actually between 0.07 and 0.18. The conservative figure of 0.05 was used.)

d_r = diameter of receiver optics aperture = 10 cm

K_R = transmission of receiver optics = 0.5

R = maximum mission range = 150 KM

Energy on PMT

$$E_R = \frac{0.128j \times 0.625 \times 0.5 \times (0.10\ m)^2 \times 0.5}{4 \times (150{,}000)^2}$$

$E_R = 2.22 \times 10^{-16}$ joules

$= 780$ photons at 6943Å

4.2.2 Probability of Detection of a Laser Return

The probability of detection of a low level signal in quantum noise is dependent on the signal level, the quantum efficiency of the PMT receiver, and the detector threshold level.

A typical transmitter laser pulse shape is shown in Figure 4-5. The number of photons in the leading eight nanoseconds (corresponding to a range variation of approximately ± 1/2 meter) is 780 x 0.37 = 290.

The PMT quantum efficiency at 6943Å is 4.4 percent minimum. The mean number of signal photoelectronic is $\bar{n} = 290 \times 0.044 = 13$. The threshold of the receiver video amplifier circuit is $n_t = 5$ photoelectrons. (Refer to Para. 4.5 on Electronic Design.)

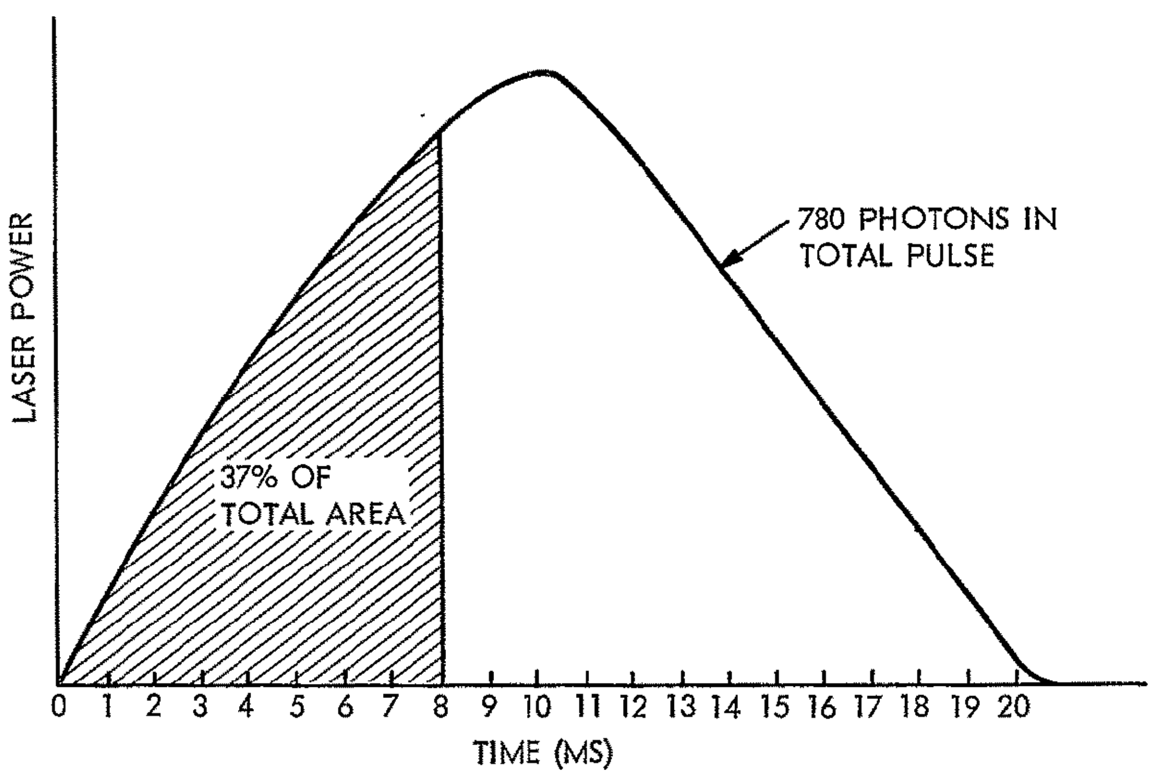


Figure 4-5. Transmitted Laser Pulse Shape

The probability of detection of a laser return during the first eight nanoseconds of the pulse is:

$$P_d = \sum_{r = n_t}^{\infty} \frac{e^{-\bar{n}} (\bar{n})^r}{r!}$$

This function has been plotted in the RCA "Electro-Optics Handbook", Page 8-7, and results in a probability of detection of

$$P_d = 0.997$$

4.2.3 False Alarm Rate

Noise sources such as lunar reflection of sunlight, dark current in the PMT, and amplifier noise combine to produce noise pulses which may cross the receiver threshold. The receiver AGC is designed to limit the noise pulse rate to 80 per second. The receiver is gated off except for a 0.5 millisecond range gate period corresponding to 40 to 80 nautical miles. Therefore, the probability that one noise pulse will occur within the range gate interval is:

$$\text{FAR} = (\text{noise pulses per second}) \times (\text{range gate duration}) \times 100\% = 4\%$$

The planned mission altitudes are 50 to 70 nautical miles. The average FAR is two percent at 60 nautical miles and three percent at 70 nautical miles.

4.2.4 Composite Performance

Figure 4-6 shows the LA performance as a function of the major system parameters. Note that the conservative value of 0.5 is used for the portion of the transmitter energy within the receiver field of view.

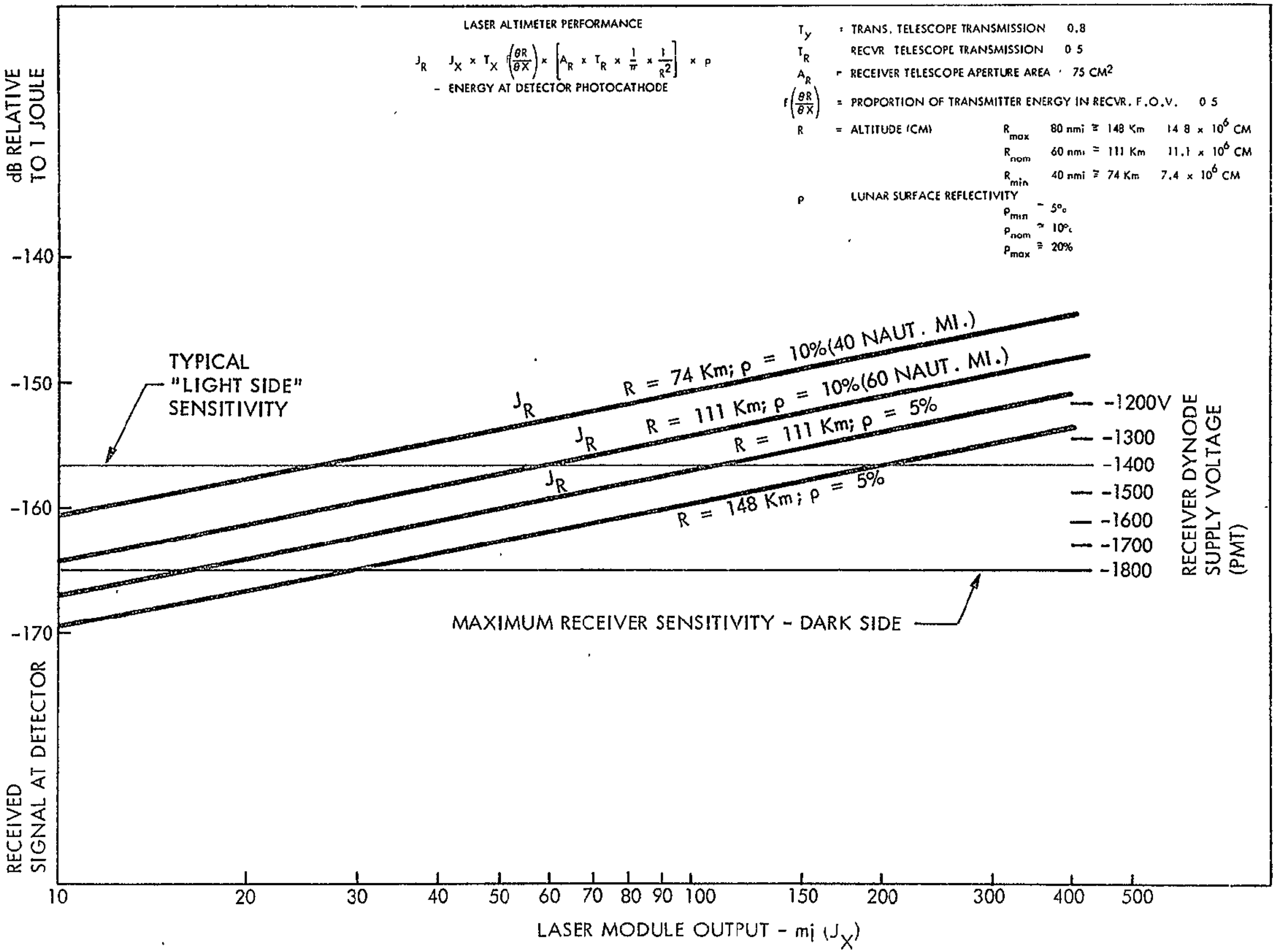


Figure 4-6. Laser Altimeter System Performance

4.3 MECHANICAL DESIGN

4.3.1 Design Constraints

The LA mechanical design evolved from a series of requirements and constraints, some of which were conflicting. The resulting configuration reflects the comprises necessary to optimize the operation of the equipment and to meet the requirements of safety, size, weight, interfaces and physical environment.

The stringent boresight stability required between the LA and the Mapping Camera (MC) made a common interface necessary. The irregular, wedge-shaped space adjacent to the Mapping Camera was the location in the SIM bay where this requirement could be achieved. The two major optical subassemblies of the LA, the telescope and the laser module, were designed to mount as close to the LA/MC interface as possible, in keeping with the requirement to minimize distortion and deflection effects.

The LA is thermally isolated from heat sinks; therefore, the dominant mode of heat transfer from electronic subassemblies is of necessity conduction to outside walls and radiation to space. This constraint made it desirable to mount the electronic subassemblies directly on outside walls of the LA to shorten heat transfer paths. The highest dissipation or most thermally sensitive subassemblies were coupled to the prime radiating surfaces.

Mission profile constraints also had a large influence upon the design. The LA is an unpressurized unit; therefore, during the launch boost phase of the flight the LA must be capable of venting from atmospheric pressure to one-pound-per-square-inch pressure in approximately ninety seconds. The opening surrounding the telescope apertures was covered by a stainless steel screen to allow venting while at the same time providing EMI integrity. This screen helped to maintain boresight stability by having low heat exchange and by minimizing mechanical coupling between the telescope and the sheet metal structure of the LA.

During EVA (Extra Vehicular Activity), the astronauts must reach across the LA to retrieve film cassettes. The outside surfaces were therefore configured to minimize danger to the astronaut. Protrusions which could snag tether lines were avoided. Specular surfaces except those necessary to the telescope were eliminated to prevent glare and solar reflections. The solar absorptivity of surfaces was controlled to prevent possible burn damage to the astronaut's suit or gloves. For additional protection to the astronauts, the telescope was designed to withstand long term solar incidence without glass breakage and the windows were recessed in the optics to minimize possible accidental breakage.

4.3.1.1 Size, Weight and Form Factor

The LA, as shown in Figures 4-1, 4-2, and 4-3, is of wedge-shaped construction 19.76 inches deep (along the optical axis) by 16.6 inches high by 14.3 inches wide. The irregular form factor of the LA was primarily determined by the available space adjoining the MC and the SIM Bay walls and by cable interfaces. The weight of all flight LA's was between 50 and 50.7 lbs.

4.3.1.2 Interfaces

The LA main mechanical interfaces are the mounting interface between the LA and MC and the plume impingement cover interface with the front of the LA telescope. These interfaces were defined by ICD Dwg. 1231-JC-2. The mounting interface consists of three mounting points. Three 5/16 inch (0.312) by 24 bolts at these points attach the LA to the Mapping Camera and provide tensile restraint. A tongue and groove joint at the rear mounting point and a 5/16 inch diameter pin at the front mounting point provide shear restraint at the interface and maintain optical boresight alignment stability between the LA and the MC.

The front and back mounting bolts and the 5/16 inch diameter shear pin insert through clearance holes in the MC and terminate in the LA. The upper mounting bolt inserts through a clearance hole in the LA and terminates in a Helicoil in the MC. There is an electrical grounding strap at the upper mounting point attached to the LA and MC by No. 10-32 screws.

The interface with the plume impingement cover required that it be close enough to protect the LA, yet not contact the LA under any condition.

4.3.1.3 Environmental Constraints

The LA design was environmentally constrained by the requirements of contract Exhibit B, the "P & I" Spec. and the negotiated ICD's. The significance of these constraints is discussed in the following paragraphs.

4.3.1.3.1 Thermal Constraints

The thermal constraint was principally the requirement to dissipate heat in a vacuum environment without external conductive or fluid interfaces. The allowable hot spot temperatures of the heat dissipating components in a hard vacuum environment and the maximum allowable thermal gradients through the structures associated with the telescope had to be controlled within this constraint.

4.3.1.3.2 EMI/Critical Pressures

The EMI requirements dictated shielding of subassemblies and of the entire assembly. The shielding, however, was designed to allow the LA to vent in order not to reach critical pressures anywhere within the assembly, precluding any high voltage breakdown.

4.3.1.3.3 Mechanical Environments

Although the design had to meet the vibration, acoustical noise, and shock criteria, analysis established that the most severe stresses were caused by induced vibration. The specified vibration levels were therefore made the basis for stress analysis and structural design. The most severe mechanical environments occur when the LA is not operating; however, the LA design had to satisfy the integrity of the transmitter to receiver boresight and of the LA optical axes to the MC interface after exposure to the mechanical environments.

4.3.2 Design Analysis and Implementation

4.3.2.1 Primary Structure

The primary structure, which consists of a "precision" 356-T6 aluminum casting (see Figure 4-7) is both the main load carrier and the optical platform for the laser module and the telescope.

The design of the structure was governed by the requirement that it meet the boresight and alignment requirements during and after exposure to the expected temperature extremes and after exposure to the specified mechanical environments. These requirements, along with the constraints of weight, cost, and schedule resulted in the selection of an aluminum structure. The requirement for a material with high stability when exposed to thermal cycling, narrowed the choice of alloys to either 2024-T3 or 356-T6.

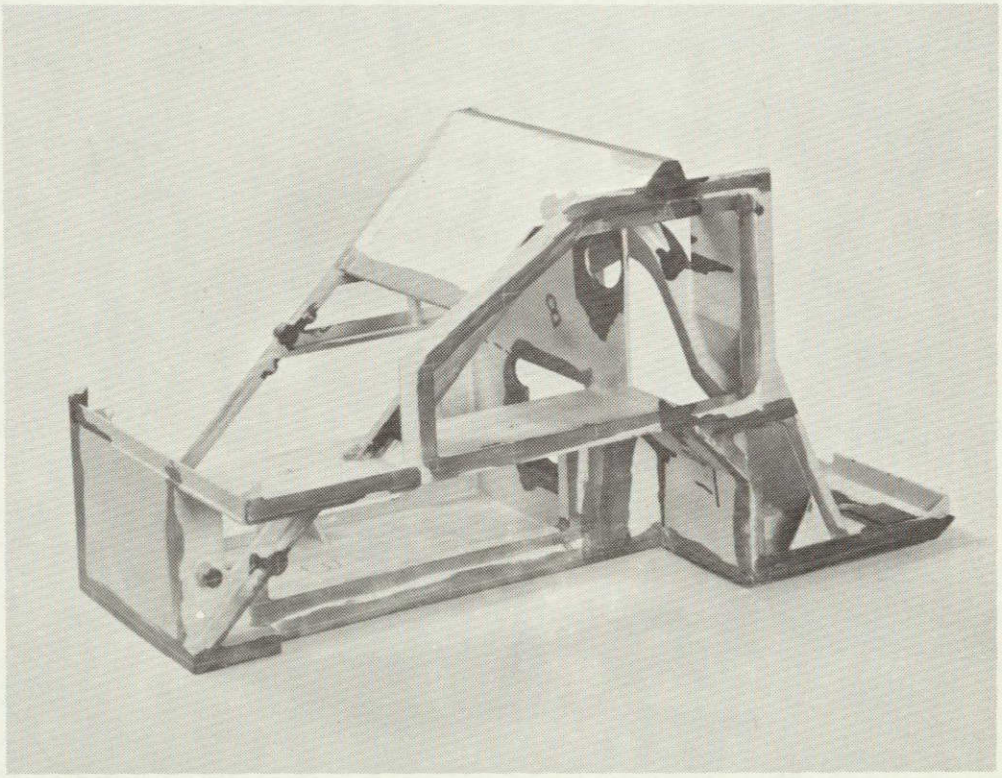


Figure 4-7. Laser Altimeter Main Casting

The optical requirements on the structure, after dynamic loading, dictated stresses below the elastic limit to preclude material hysteresis. To keep the stresses at acceptably low levels, loads were transferred almost exclusively in direct tension, compression or shear, which dictated a web truss design. For producibility the structure was cast; the 356-T6 casting alloy was chosen.

As analyzed and proven by subsequent testing, the primary structure achieved the desired and predicted stiffnesses and low stresses. The structure is highly damped due to the sheet metal shear webs riveted to the casting. The LA chassis was designed using the following criteria:

Max. allowable casting stress = 12,000 psi

$$\text{Dynamic Load } g_p = C_1 \sqrt{\pi/2 \text{ x} \rho \text{ x fn x Q x } C_2 \text{ x } C_3} \qquad (1)$$

where

C_1 = damage factor = 2.5 for this design

ρ = specified spectral density at fn

Q = amplification factor = 15 (assumed)

C_2 = specified 4 dB increase for 10 seconds

C_3 = imposed design limit of 1.69.

$$\text{The allowable static stress} = \frac{12,000}{g_p}$$

During the design phase, the specified ρ was 0.1125 g^2/Hz from 200 Hertz to 2,000 Hertz with a 3 dB/octave rolloff from 200 Hertz to 20 Hertz. The analysis clearly indicated that the stresses did not exceed the allowable levels even for the then specified spectral densities. Subsequently, it was determined that, in the bands of interest (200 Hertz and higher)

$0.1125\ g^2/Hz$ was overly pessimistic. Lower spectral densities were specified and applied in the test. Figure 4-8 delineates the curve used as the design criterion and also the finally negotiated random vibration levels.

Table 4-2 summarizes the calculated critical stresses and the allowable critical stresses both for the $0.1125\ g^2/Hz$ spectral density and the highest currently applicable spectral densities.

4.3.2.2 Secondary Structure

The secondary structure carries the load of the electronic subassemblies such as the counters, control board, high voltage power supply. It consists of a sheet metal wrap-around of 0.06 inch, 6061-T6 aluminum bolted to the primary structure, and sheet metal doors with embossed stiffeners. The design criteria for the secondary structure are the same as for the primary structure except for the following:

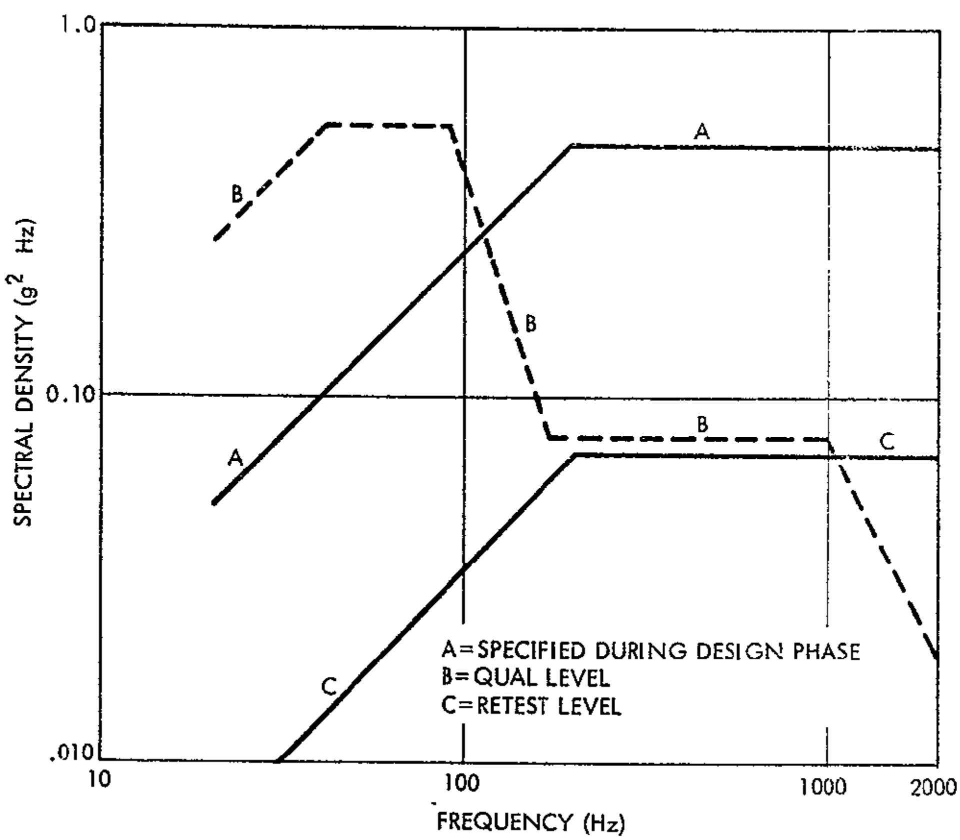


Figure 4-8. Random Vibration Inputs to LA

Table 4-2. Primary Structure Stresses

Element	fn/Axis (Hz)	Calculated Static Stress (PSI)	Allowable Static Stress (PSI)	
			Design	Applicable
Telescope Mount	200 (X)	86.5	100	252
Telescope Mount	500 (Y)	34.4	70	176
Telescope Mount	400 (Z)	62.8	76	192
Energy Storage Capacitor Mount	155 (Y)	95	130	256
Energy Storage Capacitor Mount	230 (Z)	70.2	94	237
Laser Module	Very High	Very Low	---	---

(1) The allowable static stress is based on the yield point of the material (35,000 psi) and hence is equal to $\frac{35,000}{g_p}$ (g_p is derived in Par. 4.2.2.1.).

(2) The secondary structure was decoupled from the primary structure so as not to superimpose its vibration stresses on the stresses of the primary structure.

Analyses performed during the design phase indicated that the secondary structure contained ample margin of safety even for the dynamic levels existing at that time and that the resonant frequencies were sufficiently decoupled from the primary structure.

4.3.2.3 Telescope

Although survival in the environment was a significant design consideration, the optical and thermal design tasks on the telescope were even more demanding. The telescope assembly was originally envisioned as refractive, but the cyclic thermal environment from the hot to the cold side of the moon would have caused serious optical problems. Compensation for dimensional and refractive index changes could have been effective in the steady state, but the transient states would have resulted in excessive optical aberrations. However, in a reflective telescope using low expansion coefficient glass, the thermal variations of the optics themselves could be insignificant. The reflective elements of the receiver and transmitter telescope, and the joining saddle blocks were made entirely of Cervit C-101, a very low expansion glass. The telescope refractive elements, the windows and the transmitter diverger lens, were made of optical quality fused quartz which has a similarly low expansion. The two telescope assemblies were precision epoxy bonded in a monoblock assembly. Design calculations showed that a temperature change of 100°F would cause a negligible change in the optical performance of the Cervit-fused quartz assembly. Increased transmitter telescope divergence in lunar space of 4 microradians for 100°F change of temperature of the telescope resulted from the dispersive lens focal length change with temperature.

The supporting outer housing of the telescope assembly was cast with 356-T6 aluminum alloy because of its good dimensional stability characteristics.

Although temperature effects were negligible in the reflective optics, varying thermal environment affected the support structure. Conductive heat exchange between the telescope assembly and the laser altimeter was limited by insulating the mechanical interfaces of the telescope. Radiative heat exchange was limited by polishing and gold plating the casting, inside and out. With external heat exchange thus minimized, thermal uniformity within the casting was accomplished by making the aluminum walls as heavy as possible consistent with telescope weight goals. Computer analyses were used to determine the thermal loading and to establish the proper wall thickness. In order to maintain the allowable telescope portion (30 microradians) of the optical alignment stability error budget, the temperature differential from the front of the casting to the back could not exceed 2.2F°. The required average wall thickness was determined to be 0.187 inch for the main body of the casting.

The Cervit-quartz assembly is mounted within the aluminum casting with a small clearance all around. It is secured to the casting with 0.03 inch thick RTV 566 silicone rubber. The rubber thickness was chosen to provide a good compromise between low stress due to differential expansion and high resonant frequency (approximately 400 Hz) for the mounting. The rubber joint at the front also serves as the nitrogen pressure seal for the telescope.

4.3.3 Materials

The materials used throughout the Laser Altimeter Program were taken from approved materials lists or were specifically accepted by NASA. The NASA/MSC document "Preferred Materials for Vacuum Stability Requirements for Apollo Spacecraft Applications", Rev. 0, dated February 20, 1970, and an RCA submitted memo ALT-346-083 entitled "Laser Altimeter Materials List" dated April 30, 1970, accounted for approximately 95% of the materials used on the program. All other candidate materials were submitted for NASA/MSC review.

4.4 THERMAL DESIGN

The Laser Altimeter was designed to be maintained at reliable operating temperature levels by passive cooling to its surroundings. Heat generated by the electronics is thermally conducted to the exterior Altimeter surfaces and removed by radiant heat transfer. The thermal control coating applied to the major Altimeter surfaces is SV-6. This coating has an emissivity of 0.89 and a solar absorptivity of 0.24. The Altimeter was designed for continuous operation when deployed outward about 18 inches from its stowed position and with its optical axis normal to the lunar surface. During non-operating periods the unit was stowed within the SIM bay.

The highest dissipation subassembly in the Laser Altimeter is the laser module. Laser temperature telemetry was included in the design. Analysis and thermal tests on the Altimeter indicated that temperatures of other electronics except for the photomultiplier tube, generally tracked the cavity.

4.4.1 Design Constraints

The thermal design constraints on the Laser Altimeter were:

(1) No operation of the Laser Altimeter in the stowed position.

(2) No prolonged hot or cold vehicle orientation with the Laser Altimeter in a deployed position.

(3) No operation of the Laser Altimeter above +131° F or below 30° F.

(4) No prolonged deployment of the Laser Altimeter with Altimeter power off.

(5) No plume impingement from the RCS engines without the protective covers in position.

(6) Operation only with the S/C in the "SIM Bay" attitude.

(Conditions (1), (2), (4) and (6) were not always maintained during the missions.)

4.4.2 Design Approach Implementation

The thermal design of the Laser Altimeter was implemented by thermal analysis, design tradeoffs, and tests. Thermal analysis was detailed to the individual printed wiring board component. Thermal paths between components and Laser Altimeter radiating surfaces were designed for specific thermal resistance values by component location and by the use of thermally conductive epoxies and urethanes to minimize the number of contact resistance interfaces.

The emissivities of the exterior Altimeter surfaces were selected to control the magnitude of radiant heat transfer. The Laser Altimeter surfaces facing the Mapping Camera were low emissivity (0.17) to minimize heat transfer between the Laser Altimeter and MC. The front surface of the telescope housing has a low absorptivity to minimize telescope temperature. The surfaces from which heat transfer is desired have an SV-6 thermal control coating, with an emissivity of 0.89.

4.4.3 Thermal Analytical Model

The Laser Altimeter thermal analytical model was updated several times. The last Laser Altimeter TAM, revision, ALT-330-317, reflects early SIM door jettison and the added RCS plume protective doors and covers. A total of 85 lumped mass nodes were used in the RCA TAM to establish the Laser Altimeter thermal profile. Analyses were also performed for the telescope assembly, power supplies and each of the printed wiring boards. The TAM included the Confac layouts defining the radiational view factors from the exterior Laser Altimeter surfaces, the nodal conductive and radiational networks, and tables of the thermal resistance and capacitance values of the model. The RCA TAM contained all of the data required to incorporate the RCA Laser Altimeter model into the overall SIM bay model.

4.5 OPTICAL DESIGN

4.5.1 Design Constraints

The optical design of the Laser Altimeter was predicated upon the optical constraints of the mission profile and energy output for power available. In Para. 4.1, the required beamspread, optical transmission and assumed lunar reflectivity were discussed. The design implementation to provide the required characteristics is defined in the following paragraphs.

4.5.1.1 Optical Characteristics

The raw laser beam emerging from the laser module interferometer has a 6 mm beam diameter and a beam spread of approximately 5 milliradians. The optical specification for the Laser Altimeter required that range information be determined for a 200 microradian field-of-view (FOV), of the lunar surface as seen from the LA. To allow a practical amount of boresight shift between the transmitter optical axis and the receiver optical axis without the loss of return energy, the area of lunar surface illuminated was established at 300 microradians as seen from the LA. This parameter determined that the required transmitter telescope magnification be approximately 16X:

The telescope magnification required is equal to the ratio of the beam divergence of the laser output to the required altimeter output beamspread. The magnification is therefore $\frac{5\ \text{mr}}{0.3\ \text{mr}} \cong 16$ power.

The physical optics of a telescope dictate that as the beam angle is reduced by a factor of 16, the output beam diameter is expanded by a factor of 16. The diameter of the transmitter telescope optics, therefore became approximately four inches, based on a 0.25-inch diameter laser beam.

In the interest of maintaining system symmetry and collecting adequate return energy, the diameter of the receiver telescope entrance optics was also established at four inches. These parameters were consistent with the system performance requirements as discussed in Section 4.1.1.

4.5.1.2 Environment

The optical design was so implemented that the required system performance was unaffected by the specified physical environment. The telescope was designed to withstand the specified shock and vibration inputs and the varying thermal conditions without degradation to system optical stability.

4.5.1.3 Stability

For the Laser Altimeter to perform properly, the transmitter and receiver optical axes were kept parallel to the Mapping Camera optical axis throughout the useful mission of the experiments. The receiver axis and transmitter axis were held parallel to within 50 microradians to insure that the receiver FOV was always fully illuminated by the transmitter. (Axis excursions greater than 50 microradians from true boresight could cause the receiver to "see" non-illuminated lunar surface outside the transmitter 300 microradian FOV, thus a reduced return signal.)

The receiver axis was held parallel to the MC mapping lens axis to within 210 microradians (one resolution element of the camera) to ensure that the LA provide range information for the proper point on the recorded photograph. The 210 microradian tolerance shared by the LA and MC was further apportioned to 70 microradians allowable between the LA receiver axis and the LA mounting interface, 70 microradians across the LA/MC interface, and 70 microradians from the MC interface to the MC mapping lens axis.

The Laser Altimeter satisfactorily maintained optical stability within these requirements throughout acceptance tests and qualification tests.

4.5.1.4 Weight

One severe constraint on telescope design was to achieve minimum weight. A reduction of about 1.5 lb. was achieved between prototype and flight unit telescope designs. The weight breakdown of the Laser Altimeter in flight configuration is compared in Table 4-3 with the Prototype LA weight.

4.5.2 Telescope Design

The telescope optical design comprised two sections; the transmitter telescope, and the receiver telescope which includes the checkout and alignment telescope (CAT).

4.5.2.1 Transmitter Telescope

The transmitter telescope is an a-focal beam expander which transforms a 6 mm diameter laser beam with a 5 milliradian divergence into a 4-inch diameter beam with a 300 microradian divergence. The telescope consists of a small fused quartz diverging lens, followed by a two-mirror system made of Cervit. Energy from the laser module is diverged slightly by the small meniscus lens and illuminates a 0.60 inch diameter spherical lens bonded to the front window. This mirror is so configured and located that the reflected energy from the mirror fully illuminates a 4-inch diameter mirror. This mirror has been given an ellipsoidal shape to correct for spherical aberration. Reflected energy from this mirror passes through the flat, parallel front window. The front window has been intentionally tipped slightly to prevent reflections back into the laser interferometer. The on-axis performance of the system is essentially diffraction limited.

The system inherently has a considerable amount of coma. A parallel beam in the laser space, including an angle Θ' with the axis, emerges (momentarily disregarding diffraction effects) as a beam in which the direction Θ of the rays is given by

$$\Theta' = \frac{\Theta}{16} (1-0.12p^2),$$

Table 4-3. Laser Altimeter Weight

Subassembly	Prototype SN 0001	Flight Unit SN 0003
Laser Module	7.27A	6.58A
Telescope	9.20A	7.31A
PFN Capacitor	8.02A	8.02A
PFN Inductor	0.80A	0.80A
L.V. Power Supply	2.19A	2.17A
H.V. Power Supply	3.20A	3.10A
Photomult. Power Supply	0.50A	0.50A
Control Ct. Bd.	0.63C	0.64A
Isolation & Timing Bd.	1.24A	1.16A
Video Amp. Bd.	0.40C	0.39A
Altitude Word Bd.	0.39A	0.34A
Range Counter Bds.	1.01A	0.90A
Photomult. Tube	0.40C	0.40A
EMI Filters	0.50C	0.50C
Crystal Oscillator	0.27A	0.27A
Connectors & Wiring	2.13E	1.66E
Chassis/Case/Hdwe	14.71C	14.55C
Misc. Elect.	0.80E	0.60E
Total Actual	53.61A	50.0A

Note: After each weight noted:

A = Actual
C = Calculated
E = Estimated

in which 'p' is the relative height in the exit pupil. Thus the presence of coma is beneficial to the performance of the system, in that it contracts the emerging beam into a solid angle smaller than predicted by first order theory. It follows that an angular positioning error of the laser to an amount of a few milliradians does not affect the luminous efficiency of the system.

4.5.2.2 Receiver Telescope

The receiver is a Dahl-Kirkham system with a 4-inch diameter aperture and 12-inch focal length. Light enters the receiver through the flat, parallel quartz window, is reflected by the ellipsoidal primary mirror onto the spherical mirror bonded to the front window, is reflected again and imaged onto the field stop in the focal plane. The 0.0024-inch diameter field stop allows reflected laser light from a 200 microradian area of the lunar surface to pass through to recollecting and filtering optics.

The system forward of the field stop is substantially diffraction limited on axis, with an Airy disk diameter of 0.0002 inch.

Off-axis the system has a large amount of coma. For an incident direction including a small angle θ with the meridional ray intercepts in the focal plane are given by:

$$x' = 120\left(1 + 0.12\ p^2\right)$$

in which p is the relative ray height in the exit pupil. The coma determines the centering to tolerance for the pinhole. Considering the structure of the coma flare, virtually no light will be lost by allowing the point of the pinhole most distant to the axis to exhibit a coma flare with a length one-quarter of the pinhole diameter. This allows a centering tolerance of ±0.004 inch. This tolerance is, however, more critically established by the centering of the receiver with the transmitter. The actual centering tolerance to accommodate both requirements is ±0.002 inch.

Behind the field stop the light is recollimated by a small lens, filtered by a bandpass filter peaked for 6943 Å energy, and refocused through a secondary glare stop onto the photomultiplier tube face.

The checkout and alignment telescope (CAT) is a part of the receiver telescope which bypasses the main reflective optics and field stop. It is used for preflight checkout and alignment of the system. A small beam splitting mirror may be manually actuated into the receiver optical path between the collimating lens and the bandpass filter to allow light from an external source to enter the system. In the alignment mode, light passes through the CAT and backlights the field stop to establish the receiver axis for boresight and alignment stability testing. In the checkout mode, a simulated return laser pulse is produced by a light emitting diode (LED) in the Ground Support Equipment (GSE), introduced into the optics, filtered and received by the photomultiplier tube as a stop pulse. Actuation of the mirror is accomplished by a small key. With the key inserted and positioned, the mirror is drawn into the optical path. When the key is removed in the flight position, the mirror is prevented from entering the optical path by a spring-loaded tumbler. Thus the beam splitter mirror cannot enter the optical path in the flight position.

4.6 ELECTRONIC DESIGN

The subassembly drawing breakdown of Figure 4-9 conforms closely to the functional electronic subassembly breakdown which evolved from the electronic design discussed in this section.

4.6.1 Design Constraints

The physical and electronic characteristics of the Laser Altimeter were dictated by Exhibit B of the contract, the ICD documents negotiated with N/R, FSDS and MSC, and the Performance and Interface Specification SD 69-315.

Parts were selected for conformance to space program reliability and for minimum weight in the specific circuit application. Components identical or similar to those used in previous space program were utilized where applicable; others were subjected to rigorous burn-in and screening tests.

Weight and size specifications were met by tradeoff studies relative to circuit grouping and subassembly location. Circuits were grouped within specific subassemblies by function

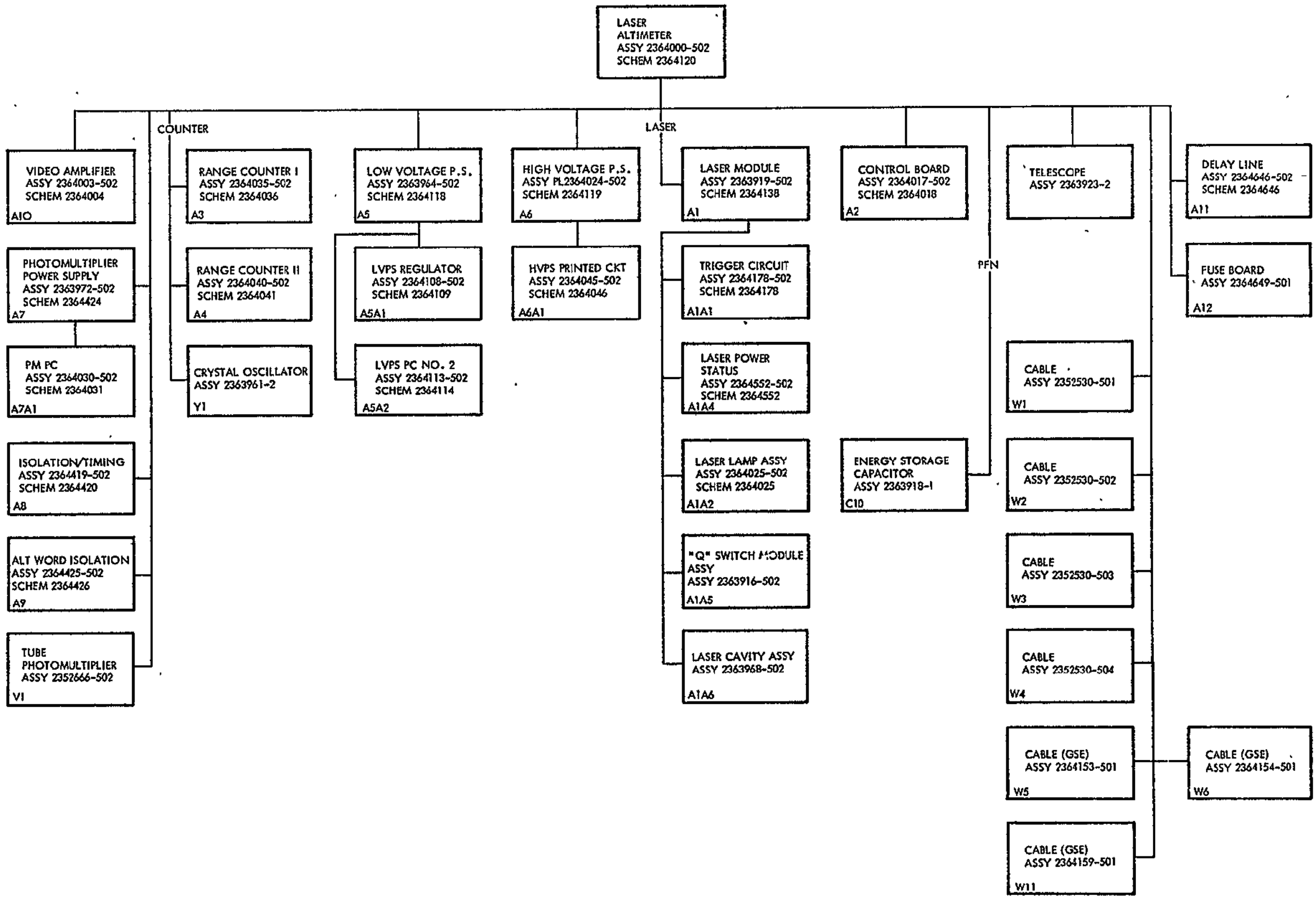


Figure 4-9. Laser Altimeter Drawing Tree

to minimize interconnection. Subassembly locations were selected to minimize length of cable runs and to provide adequate heat transfer to the main structure.

Heat transfer requirements and total power consumption were reduced by "power supply gating" so that specific circuits and subassemblies are powered "on" only when their operation is required.

Consideration was also given to filtering, noise isolation, accessibility and signal flow in location and orientation of electronics within the Laser Altimeter. All subassemblies were totally enclosed to reduce the effects of radiated interference. Crosstalk on power supply lines was further reduced by providing separate output lines to each subassembly from a totally enclosed, plug-in low voltage power supply.

The high voltage power supply and associated high energy components were located in a separate compartment remote from the high speed digital control and analog circuits. Specific potting and encapsulation techniques were applied to high voltage components and terminations to minimize the possibility of corona and voltage breakdown.

4.6.1.1 Packaging Considerations and Approach

The circuit packaging approach used etched boards insofar as possible for ease of construction and reasonable packaging density. Each circuit was laid out in uniform modular pattern with adequate consideration for conduction heat transfer paths and EMI shielding. Double-sided boards with plated through holes and feed through stitches (or leads) were used. Wiring was organized for logical flow, minimized noise, access, and to facilitate harnessing.

All significantly dissipative electronic subassemblies were mounted to the inside of externally radiative surfaces or were directly installed as externally radiative surfaces.

To facilitate removal and replacement, and because of the large number of convection paths, the low voltage power supply was designed as a plug-in assembly. The Laser Module was designed as a pressurized assembly which used an hermetically sealed connector for all low voltage connections. Hermetic bushings were used for the high voltage input. All other subassemblies were hard wired in the interest of weight minimization and reliability.

The pulse forming network and the High Voltage Power Supply were adjacent for optimum high voltage wire routing and minimum noise. The High Voltage Power Supply mounted directly to the access cover for good heat transfer and was flexibly wired to the main chassis. High dissipation and bulky components were mounted directly to the chassis using thermally conductive adhesives.

The Video Amplifier, Counter Modules, Control Board and Altitude Word Subassemblies were of similar construction and were mounted directly to exterior walls or to conducting structure to radiative surfaces.

The Isolation and Timing Assembly was trapezoidal in shape and was mounted to the inside of externally radiating structure.

The Photomultiplier Power Supply was assembled into a shielded box and mounted on a thermally conducting truss member.

Access to the electronic assemblies was through hinged access doors. Optical alignment of the Laser Module and the telescope relative to the MC mounting interface was achievable externally by means of removable pivot pins and clearance in the mounting holes.

Size of all subassemblies was minimized to the extent compatible with other constraints to achieve the 50 pound weight limit for flight units. (With the later addition of the PRF controller the weight increased by about 0.5 pounds.)

The weight of individual electronic assemblies is noted in Table 4-3.

Design calculations and measurements of the prototype LA indicated that unit weight would exceed the 50 pound limit by about four pounds. A stringent weight reduction program was successful in reducing flight altimeters weight to 50 pounds. The most effective reductions were accomplished by using thinner sections in less critical areas of telescope and laser module structure and by reduction in size of signal interconnecting wiring from No. 22 to No. 26 wire.

4.6.1.2 Thermal and Structural Constraints on Electronic Design

4.6.1.2.1 Thermal Approach

No fluid or coolant interfaces with the vehicle were permitted by specification; pressurization to allow convection cooling was precluded by the weight limit. Therefore, the Laser Altimeter electronics were maintained at reliable operating temperature by conduction from the dissipative components to the Altimeter radiating surfaces. Board layouts and component types were chosen to provide a satisfactory tradeoff between circuit and thermal requirements. The higher dissipation components were located for minimum thermal path length to the radiating surfaces. Etched pad widths and copper surface areas were maximized on boards to promote thermal spreading and reduce temperature gradients between component hot spots and radiating surfaces. The largest temperature gradient between any component and its radiating surface was 72°F on the Photomultiplier Power Supply board, resulting in maximum component temperature of 130°F.

4.6.1.2.2 Structural

The design did not require the usual electrical components (resistors, transistors) to withstand g level capabilities in excess of the usual 10 to 15 g over the 2 kHz bandwidth. Component natural frequencies were very high relative to mounting plane resonances; thus, adequate decoupling was achieved.

Components having significant mass were specified to withstand at least 10 g up to 2 kHz; lowest allowable resonant frequency was also specified to be well above the expected resonant frequency of the mounting structure. For example, the crystal oscillator specified the first resonance mode to be no lower than 600 Hz. The structure to which it was mounted had a predicted frequency of approximately 200 Hz.

This decoupling philosophy was implemented on all of the components.

4.6.1.3 Pressure

The electronics of the Laser Altimeter was designed to operate in an atmospheric pressure of 10^{-3} to 10^{-6} TORR. High voltage components were laid out and coated or encapsulated as required to meet the pressure environment. The encapsulant used was General Electric RTV 566, similar to RTV 66, chosen because of its extremely low volatility. GE silicone SE 9090 rubber insulation was chosen for all high voltage wiring because of its excellent high voltage properties and its compatibility with RTV 566.

4.6.1.4 Interfaces

The major electrical interface constraints were:

(1) All signal inputs and outputs were to be isolated from LA circuit ground.

(2) All prime power inputs were to be isolated from LA circuit ground.

(3) The maximum dc power consumption for the LA was to be less than 52 watts average and 98 watts peak.

(4) The Electromagnetic Compatibility of the LA was to be measured against the requirements of the Performance and Interface Specification SD 69-315.

(5) The LA had to provide a 24 bit serial word to the spacecraft scientific data system, consisting of 18 bits of range information and 6 bits of LA status.

(6) The LA had to provide a 20 bit serial word to the Mapping Camera, consisting of 18 bits of range information and 2 reference bits.

4.6.2 Design Implementation

A block diagram of the Laser Altimeter showing the signal and control outputs, the signal and prime power inputs, and the electronic circuits is shown in Figure 4-10. A timing diagram for the Laser Altimeter is shown in Figure 4-11.

With reference to Figures 4-10 and 4-11, the power control signal energizes K1 passing 28 Vdc to the low voltage, photomultiplier and high voltage power supplies and 115 VAC to the Q-switch motor. The pulse forming network (PFN) charges in approximately 10 seconds, at which time the Charge Enable signal disables the high voltage power supply.

The LA operates in either the Camera or Automatic mode. In Camera mode (K2 closed), the Pretrigger signal enables power to the range counter and the MC Data Request signal

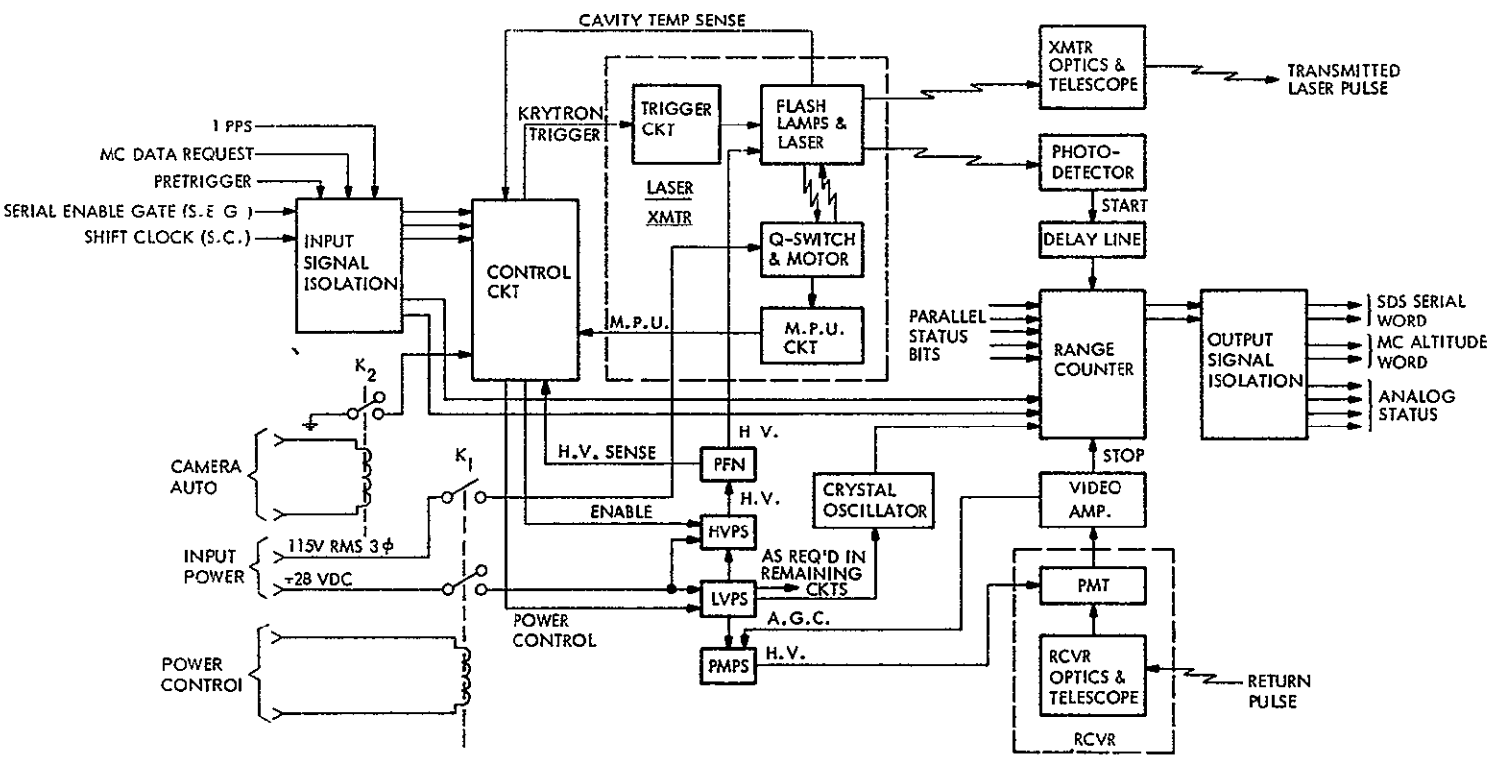


Figure 4-10. Laser Altimeter Block Diagram

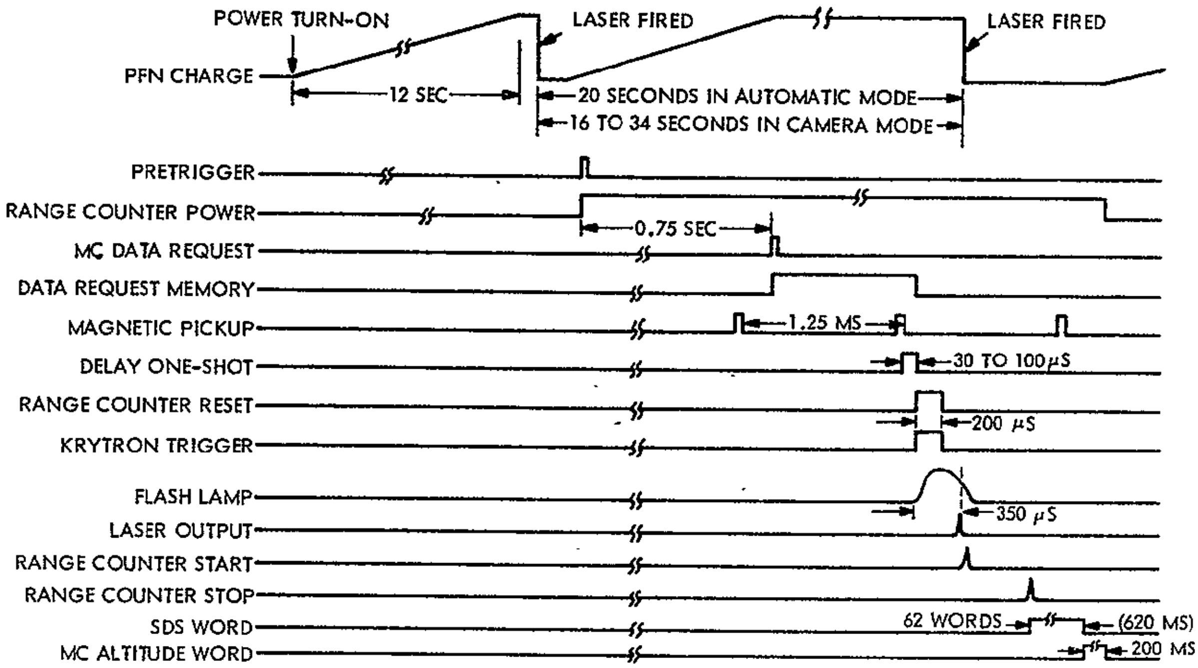


Figure 4-11. Laser Altimeter Timing Diagram

initiates laser firing. In Automatic mode (K2 open), the One-PPS signal in the control circuits initiates laser firing.

When the Kryton signal is received from the control circuit, the pulse forming network (PFN) discharges through the ionized flash lamps, producing a light pulse of 350 microseconds. This light pumps the ruby rod to a condition that permits light amplification. At the time of maximum energy storage in the rod, the Q-switch (which is a rapidly rotating prism), moves into angular alignment with the output resonant reflector. This alignment creates feedback with resulting oscillation in the ruby rod to produce an output laser pulse of 13 nanoseconds at half amplitude. The laser beam at the resonant reflector has a diameter of 0.25 inch and a divergence of 5 milliradians. A 16 power Galilean telescope expands the transmitted beam to four-inch diameter with about 0.3 milliradian beamwidth, the radiated transmitter output.

A portion of the laser output pulse is detected by a photodiode to generate a Start signal for the range counter, which has been in the reset state during flash lamp operation. The start signal is delayed through a delay line, adjusted to compensate for the delay of the return pulse through the photomultiplier tube (PMT) and video amplifier.

The return pulse is delayed by the time required for the laser pulse to travel to and from the lunar surface, and is detected by the PMT through the LA receiving telescope. The PMT electrical output is amplified in the video amplifier and becomes the Stop Pulse for the range counter. Between start and stop pulses the range counter counts cycles of 6.67 nanoseconds spacing (1 meter) supplied by a master crystal oscillator (149.8962 MHz). The number of cycles counted corresponds to altitude in meters.

The range measurement and LA status data is then clocked out as a serial word to the scientific data system (SDS). A complete definition of this word is provided in Table 4-4. Only the altitude information is sent to the MC. A complete definition of this word is provided in Figure 4-12.

All spacecraft inputs and outputs are completely isolated from LA circuit ground. Serial Enable and Shift Clock Signals are needed to synchronize the SDS Word to the data system. The analog status data output is defined in Table 4-5.

The LA provides certain equipment status outputs. Digital data (Table 4-4) consists of 18 bits of range data and six bits of equipment status. Analog data (Table 4-5) consists of equipment status and remains available during equipment operation.

4.6.2.1 High Voltage Power Supply

A dc-to-dc converter operating at a frequency of 20 kHz was used to convert the input dc voltage (27.5 ±2.5V) to the high voltage levels necessary for the flash lamps of the Laser. The dc supply voltage is converted to an ac square wave by a transistor chopper. An impedance matching filter, transformer, and high voltage rectifier were used to develop the high voltage to charge the energy storage capacitors.

Table 4-4. Digital Data

Parameter	Logical "1" Condition	Logical "0" Condition	Bit Position
Regulated +5 vdc	Regulated voltage present	Regulated voltage absent	1
Range overflow	Invalid range measurement	Valid range measurement *	2
Laser output	Laser output exceeds threshold level	Output below threshold *	3
Q-Switch motor status	Normal operating condition	Non-operating condition	4
Krytron trigger	Trigger signal applied to laser module	Trigger signal absent *	5
MC data request	Receipt of MC Data Request signal	MC Data Request signal absent *	6

* Bit positions 2, 3, 5, and 6 are reset to zero prior to the start of each range measurement. The digital serial data will be available for approximately 620 milliseconds out of each laser cycle, beginning at 30 plus or minus 10 milliseconds after laser firing.

The 18 bit altitude word is direct altitude in meters utilizing the natural binary number system.

The serial data format (order of bit transmission) is as follows:

Bit number						LSB																	MSB
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Bits 1–6: ← Equipment Status →
Bits 7–24: ← Altitude Word →

Table 4-5. Analog Data

Monitored Parameter	Parameter Range	Scaling Factor	Voltage Range
Regulated -5 vdc	Not Applicable	5 vdc = regulated voltage present; 0 vdc = regulated voltage absent	1 ± 1 vdc or 4 ± 1 vdc (Discrete)
Photomultiplier voltage	0 to -1800v	360v./v.	0 to 5 vdc
Pulse forming network voltage	0 to +3000v	600v./v.	0 to 5 vdc
Laser cavity temperature	-13 to +167°F	36°F/v	0 to 5 vdc

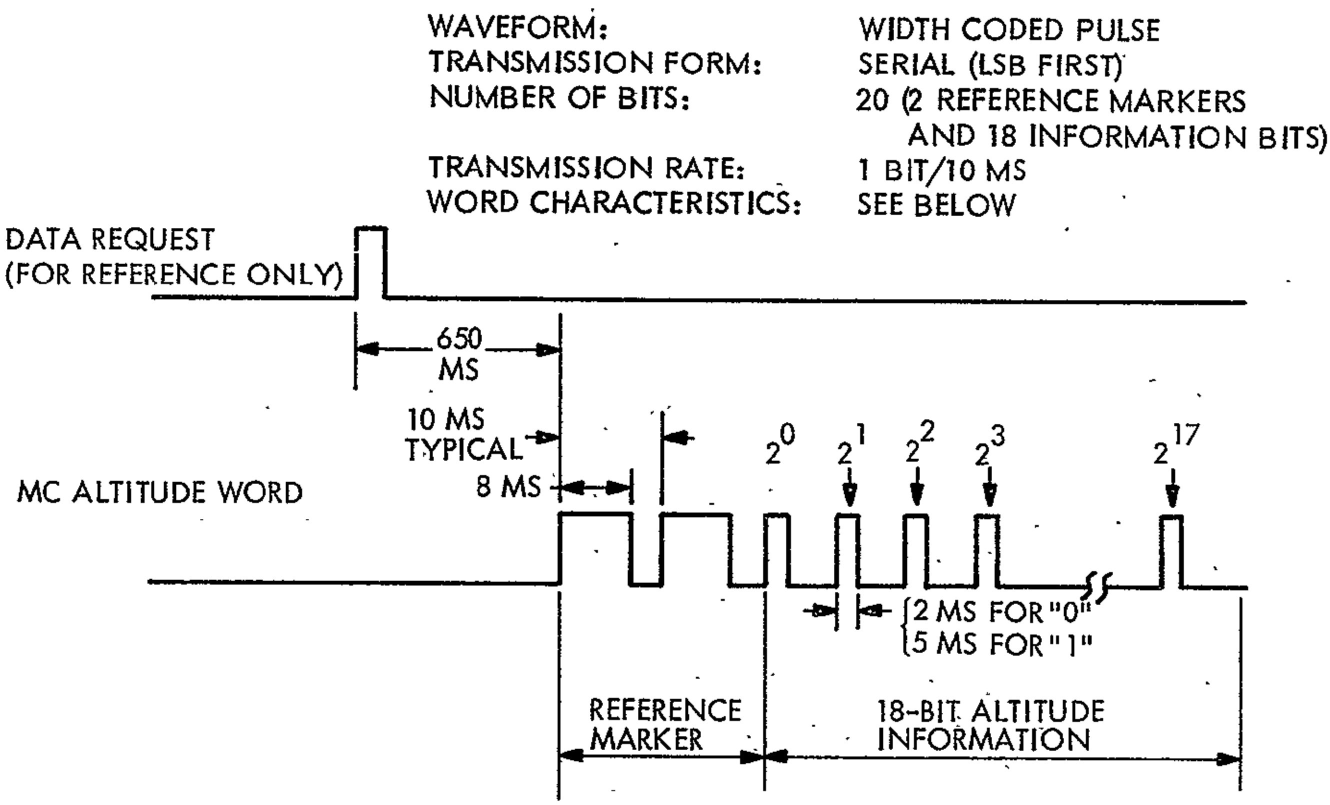


Figure 4-12. Mapping Camera Altitude Word Structure

The reactive impedance matching filter allows the energy to flow from the chopper to the energy storage capacitor with minimum loss.

4.6.2.2 Low Voltage Power Supply

A dc-to-dc converter generates the regulated voltages needed for control and counting functions in the LA. A saturating push-pull oscillator, operating at 20 kHz drives the power stage of the converter. The power stage is switched by a pre-regulator to produce a step width modulated output waveform. The time position of the step, varied by a feedback loop, provides regulation for both load and line voltage changes. Step width regulation was chosen in preference to other techniques, such as pulse width modulation, because it provides high efficiency regulation at minimum ripple. The power stage transformer output is rectified and fed to integrated circuit series regulators. The step width pre-regulator maintains approximately 1 volt drop across the series regulator pass transistors for all line and load conditions.

The series regulator outputs which provide power for counting are electronically switched on just prior to laser firing and off immediately after serial words are sent to the scientific data system and Mapping Camera, yielding an on-time of 2 seconds. Limiting the duty cycle of these supplies saves approximately 15 watts of average power dissipation.

4.6.2.3 Range Counter

The counter circuitry consists principally of: (1) a crystal controlled oscillator to generate time increments (clock pulses) each equivalent to the round trip time for light to travel a distance of one meter; (2) an integrated circuit counter to count and store the number of clock pulses which occur during the round trip time between LA and lunar surface; (3) a multiplexing circuit to convert the parallel altitude data to serial data output for both the Mapping Camera and the SDS. The counter circuit also includes minimum (40 nautical miles) and maximum (80 nautical miles) altitude gating circuits, counter reset drives, and fault indication circuitry.

The Counter Reset signal, generated in the Control circuit at the time of flash lamp triggering, is fed into the power driver gates in the counter circuit. The reset signal holds the counter flip-flops in the reset state during the flash lamp firing period just prior to the start pulse.

The start pulse is detected by a photo diode in the laser, which changes the state of a flip-flop, thereby enabling the clock pulses from the 150 MHz oscillator to be gated into the counter where they are counted in binary. The first return or echo pulse received from beyond the minimum altitude (74 km) will stop counting and retain the count in binary form. If no return pulse is received, the counter circuit will automatically reset when the count reaches the maximum range gate limit. Minimum and maximum altitude measurement are fixed in this manner to minimize the receiver acceptance time and false alarm proaability.

The parallel binary altitude information from the counter is stored in latching circuits which also buffer the counter output from the multiplexers.

The multiplexer circuitry converts the parallel binary data into serial binary form. Equipment status (6 bits) is also processed into serial form by the multiplexer circuits.

Multiplexer timing is accomplished using an external 100 Hz Enable Gate, 64 kHz shift clock, and three internally generated 100 Hz multiplexer clocks. One phase of the 400 Hz 3 phase power is used to generate the three 100 Hz signals. Special logic is used to insure proper range word generation since the external and internal 100 Hz multiplexer signals are not synchronized.

The counter start and stop logic uses ECL elements with propagation delay of 1 nanosecond per element. The range error jitter contributed by the counter is less than 1 nanosecond.

4.6.2.4 Receiver Video Chain

The laser signal return from the lunar surface is incident on the Photomultiplier Tube (PMT) photocathode. Photoelectrons thus released are amplified by a 10 stage electron multiplier.

The resulting current flows through a load capacitance and resistance. The two stage differential video amplifier drives an output transistor switch which generates the Range Counter stop pulse. The same output is used for AGC. Noise pulses from lunar background and PMT which exceed the video output threshold are integrated producing a DC voltage which controls the PMT high voltage and gain. The AGC maintains a False Alarm Rate (FAR) of less than 4 percent.

4.6.2.4.1 Photomultiplier Tube

Characteristics of the PMT are shown in Table 4-6. and Figure 4-13. The anode sensitivity of the PMT is relatively constant with temperature, varying less than 10 percent, from +22°C to +55°C. The photocathode material is an extended red multialkali (ERMA) to obtain relatively high quantum efficiency at 6943 Å.

Table 4-6. Photomultiplier Tube Characteristics

Quantum Efficiency		4.4% Minimum @ 6943 Å
Sensitivity	22°C	0.7 to 1.4 x 10^4 amperes/watt @ 6943 Å
	55°C	within ± 10% of above value
Dark Current	22°C	< 25 pps @ 5 photoelectron threshold
Spectrum	55°C	< 40 pps @ 5 photoelectron threshold

4.6.2.4.2 Video Threshold

Range Counter stop signals are generated when 5 photoelectrons are emitted from the photocathode within an integration period of 20 nanoseconds. The PMT voltage is set between the level required to obtain the anode sensitivity of Table 4-6 and the maximum of -1800 Vdc.

4.6.2.5 Photomultiplier Power Supply (PMPS)

The PMPS converts the +6 to +12 VAGC control voltage to a proportional high voltage of -900 to -1800 Vdc. This voltage supplies the photocathode and 0.25 ma dynode divider string for

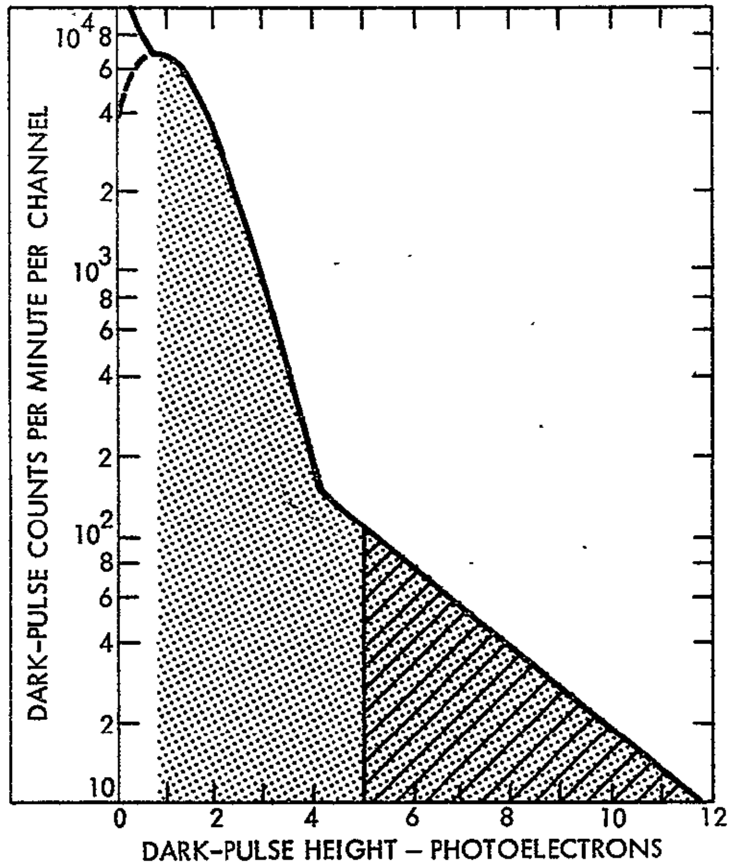


Figure 4-13. Photomultiplier Tube Dark Noise Characteristics

the PMT. The AGC signal is scaled to drive a series regulator for a 20 kHz chopper, step-up transformer, and voltage doubler circuit. The PMPS is inherently short circuit protected for short duration faults and is well filtered to minimize 20 kHz noise.

4.6.3 Parts Selection

Flight hardware parts were selected according to the following priorities:

(1) Established reliability parts.

(2) Parts used in previous space programs. Past experience in designing systems for space programs, particularly for the LM provided a catalog of parts suitable for space environment. This source was included in the selection of components for the Laser Altimeter .

(3) Military approved parts. Military approved parts were used in the Laser Altimeter with rigorous screening and burn-in test requirements added to assure reliable system operation.

(4) Commercial and Special Parts. Parts having no previous qualification status were defined by Specification which imposed tests to control the characteristics of the components and to require screening and burn-in to assure stability and reliability.

Category 4 parts included solid-state devices, many integrated circuits, magnetic components, flash lamps and motors. The motor, flash lamps, and associated laser parts had been used in ground and airborne military systems and had extensive testing. The techniques, information and data gleaned in tests of previous systems were used in the design and fabrication of the Laser Altimeter.

4.7 LASER DESIGN

4.7.1 Design Constraints

Operation in a space environment imposed the following constraints on the Laser Module:

Bearings	Low friction high speed bearings were required in the "Q' switch; the oil-grease lubricant had to be protected from high vacuum conditions with resulting evaporation causing loss of lubrication and with resulting bearing failure. Additionally, deposits of petroleum products on critical optical surfaces could reduce efficiency or cause malfunction.
High Voltage	The high voltage circuits - (energy discharge 2500V and trigger circuits - 25 K.V.) could break down in critical pressure conditions.
Cooling	The only modes of heat transfer available to the laser module were radiation or conduction to a radiating surface. Heat from the laser pump lamp and "Q" switch motor had therefore to be conducted to a radiational surface.

Stability — Dimensional stability of the transmitter had to be maintained when subject to temperature variation and dynamic stresses.

Optics, particularly the exit window (resonant reflector) could not be permitted to degrade as a function of temperature and pressure variations.

4.7.1.1 Performance Requirements

The performance requirements derived from system analysis were the following:

Output Energy:	300 millijoules
Beam Divergence:	5 Milliradians max.
Pulsewidth:	13 nanosec. (1/2 power point)
Rise Time:	8 nanosec. (10-90 percent points)
Pulse Rep. Rate:	3.75 pulses per minute max.
Life:	50,000 operations
Output Frequency:	0.6943 micrometers

4.7.1.2 Environmental

The following environmental characteristics were significant:

Temperature	+32°F to +131°F operating
	-40°F to +160°F transportation and storage
Pressure	10^{-6} to 10^{-3} Torr and 760 Torr
Shock and Vibration	As integrated in the LA

4.7.2 Design Implementation

Functional assemblies in the laser module are the following:

(1) Laser system (head, Q-switch and prisms, and resonant reflector)

(2) Trigger transformer

(3) Trigger circuit

(4) Mag. pick-up amplifier

(5) Photodiode and amplifier

(6) Trigger signal amplifier

Figures 4-14 and 4-15 depict an engineering model of the laser module, generally similar to the flight unit configuration.

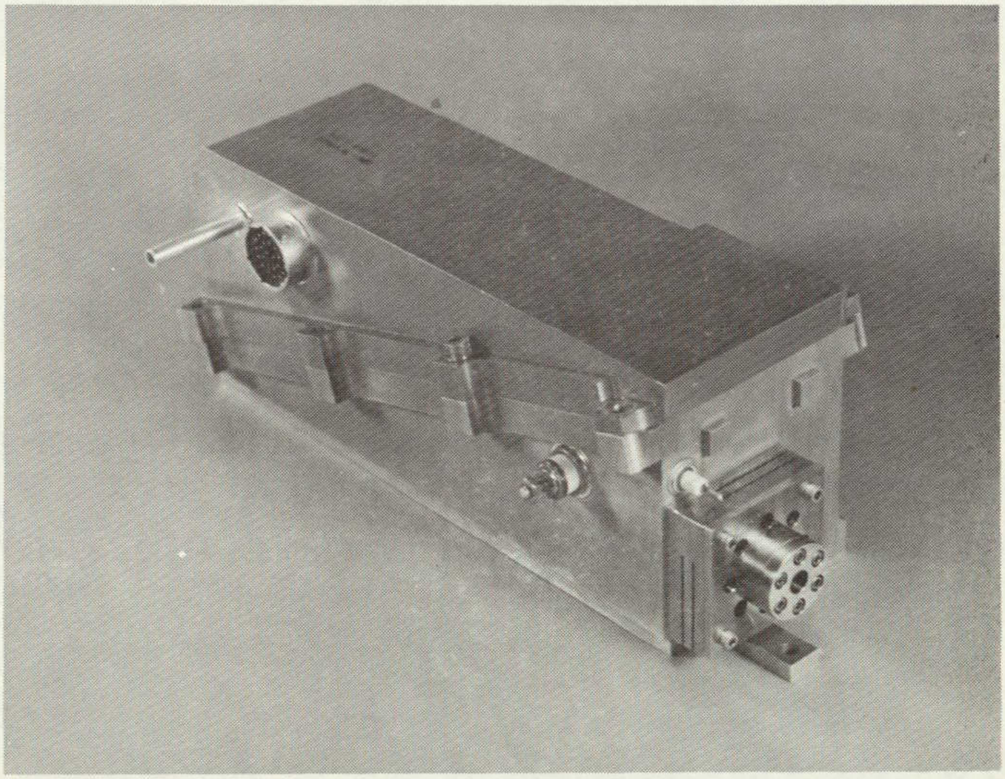


Figure 4-14. Laser Module Engineering Model - Exterior

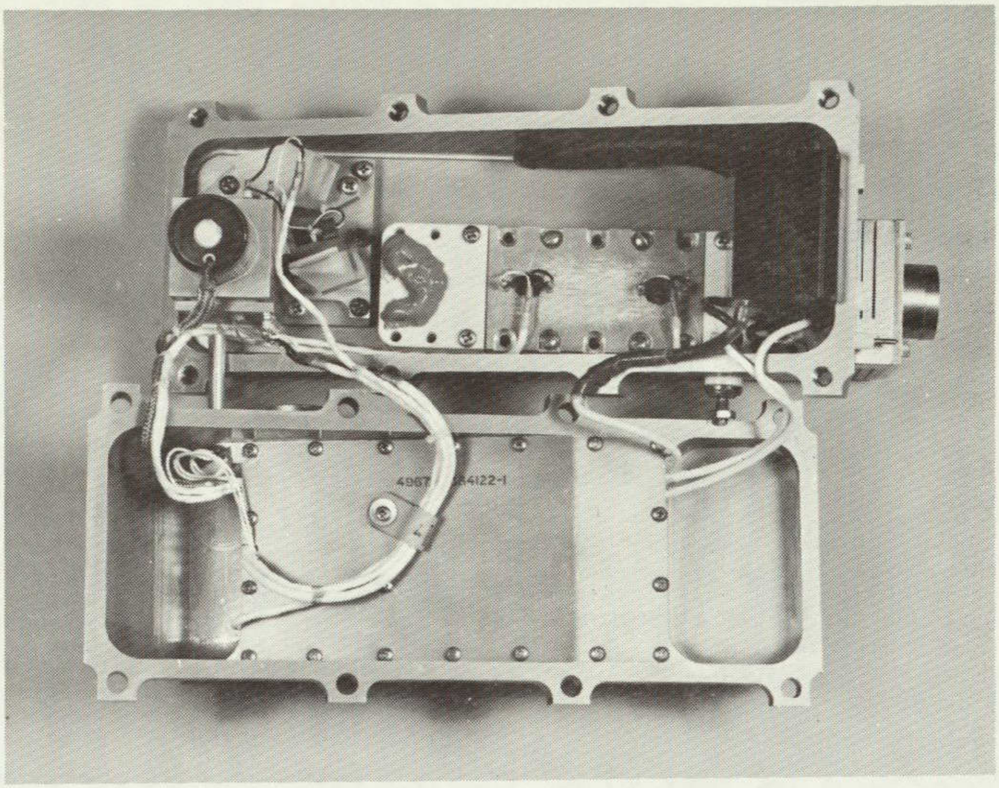


Figure 4-15. Laser Module Engineering Model - Interior

4.7.2.1 Interferometer Layout

The interferometer length of 16 inches provides a reasonable compromise of beam spread and efficiency. A resonant reflector is used as the output coupler to provide stability and freedom from optical damage. The 16-inch interferometer length is achieved by folding the rear or "Q" switch portion of the interferometer. The laser beam passes through a Brewster entry and exit Q-switch prism, rotating at 24,000 RPM, enters at Brewster's angle the elevator prism (which raises the beam axis and reflector to pass through the Q-switch prism again). A Brewstered porro prism is the rear retroflector of the Fabry-Perot interferometer. The beam is then reflected back on its original optic path, through the Q-switch prism and rod. The folded optical path through the Q-switch provided long interferometer in a small space and extremely fast switching at relatively low prism speed.

4.7.2.2 EMI/RFI

The Laser Module contains circuits operating at millivolt levels and circuits operating at several kilovolts, with peak currents approaching 1000 Amps. To minimize interference, the flash lamp circuit was grounded only at the PFN capacitor, external to the module. The number of wires in and out of the housing was kept to a minimum and two conductor shielded wire was used where necessary.

All low level signal processing circuits were housed in shielded sections of the module cover to separate them as much as possible from the high voltage, high current circuits. Output signals are amplified to standard logic levels within the module. Power circuits are decoupled to minimize interaction.

4.7.2.3 Module Stiffness

The laser module has 0.250 inch basic wall thickness, ribbed to minimize weight, yet provide the optically stable base needed for the laser, The Q-switch assembly is rigid with tolerances such that precise adjustment in the less critical axis is eliminated, to provide maximum rigidity to the entire optical section. The Q-switch elevator and porro prisms are mounted together as a subassembly and are pre-aligned prior to installation in the module.

The joint between the base and the cover of the module is an angle with base high in front and low in the rear. This provides a rigid support for the resonant reflector and accessibility to the Q-switch components for adjustment or cleaning, without the aid of special tools. The resonant reflector adjustments are external so that minor adjustment with the module sealed and pressurized is possible.

4.7.2.4 Laser Crystal Sizing

The size of the laser rod, chosen to provide the required output energy with adequate margin, was 1/4 inch diameter by three inches long. Rods of this size with excellent optical quality (one fringe or less in the three inches) were available from several sources and could provide a 3 dB margin in output.

4.7.2.5 Differential Temperature

The laser module structure is primarily of aluminum mounted on aluminum so that stresses due to thermal differentials are minimized.

Exceptions are prisms and mounts and the laser rod-pump cavity where greater differentials appear. The rotating prism and laser rod are compressively loaded below the optical strain point.

4.7.2.6 Bearing Lubrication

The bearings in the Q-switch were conventional, hi speed, low friction ball bearings with the proper lubrication for the temperature ranges anticipated. Special "Space Rated" bearings were not necessary as the module leak rates are low enough to guarantee a protective atmosphere. However, contamination of optical elements by lubricant resulted in the use of sealed, grease filled bearings for Apollo 16. For Apollo 17 bearing lubrication was limited to oil impregnation of the phenolic ball retainer. TFE fiberglass seals were incorporated in the bearings.

4.7.2.7 Vacuum Seal

The Laser Module was pressurized and sealed to prevent high voltage breakdown and bearing lubrication evaporation. This environment allowed the use of standard laser techniques for wiring, triggering, and Q-switching.

To achieve the desired seal with low leakage rate, the cover for the module used a Viton "O" Ring seal. The leak rate for this seal is specified as less than 10^{-9} cc/sec. of helium. The exit window and cover used the same sealing arrangement. The output of the PFN was fed to the module through hermetically sealed ceramic bushings rated at 6 KVAC at sea level.

A hermetically sealed Cannon connector was used for the low voltage and signal leads. The published leak rate for a solder shell connector is 0.001 micron - cu. ft./hr. of helium. This is about 10^{-8} cc/sec. which is the highest predicted leak rate in the module. Leakage during the mission life of about 230 hours is completely negligible.

4.7.2.8 Inert Gas Fill and Pressurization

A Schraeder valve was provided to fill, pressurize and check the laser module. High purity dry nitrogen was introduced after purging, at a pressure af about 3 psi above atmosphere. The absolute pressure was approximately 17 psi in the module during the mission.

4.7.2.9 Output Window

The sealed resonant reflector assembly was used for the output window. The thickness of each of the two fused silica etalons was 0.125 inches. They were separated by an invar ring spacer of equal thickness. This assembly formed the front reflector of the laser interferometer.

4.7.2.10 Trigger Circuit

The trigger transformer that was chosen for this laser system was similar to one used on another system for 50 cm pressure lamps at much higher duty cycle. As a consequence the rating was conservative in the LA application.

4.8 GROUND SUPPORT EQUIPMENT

4.8.1 Design Constraints

Numerous constraints on the design of the GSE were imposed by ICD's and by the particular problems associated with testing the LA. Size, weight, form factor, external electrical interfaces and environmental considerations were dictated by NR ICD. Optical and electrical interfaces with the LA were governed by ease of installation, alignment and minimization of cables.

4.8.1.1 Size, Weight, Form Factor

The negotiated interface spec., NR ICD MH01-12914-234 set forth the external details of the GSE. It called for a two unit approach, one of which was relatively small and light to be placed close to the LA to provide the optical interface. The other unit was larger and heavier, provided all operating controls, and could be located up to 45 feet away from the LA.

4.8.1.2 Interfaces

The GSE had to interface with facility power and grounding systems at KSC, and with the LA, mechanically, electrically and optically. Optical and electrical interfaces were required when the LA was operated separately on the bench, after LA mounting to the MC on the LA/MC handling fixture, and also when the LA/MC assembly was installed in the spacecraft. The GSE/LA electrical interface provided for control and powering of the LA either from the GSE prior to spacecraft installation or from the CSM with the LA installed in the SIM bay.

4.8.1.3 Environment

The GSE was required to operate only in a controlled environment where the temperature was maintained between +60°F and +80°F. The thermal design was therefore greatly simplified.

4.8.2 Design Concept

The GSE was separated into two main units; the Electronics Unit (EU) and the Receiver/Transmitter (R/T). The R/T contained a small removable optics module to attach to the LA and provide the optical paths.

This particular configuration was chosen to meet the handling and use requirements of testing the LA when mounted in the spacecraft. In operation the GSE triggers and senses the LA output. If the output exceeds the energy level required to range from lunar orbit, the GSE generates after a pre-selected time delay, an optical pulse similar in wavelength and shape to the LA output pulse. This GSE pulse is introduced into the LA receiver and is of the same approximate energy level as the pulse expected to be received during operation in lunar orbit. The GSE then displays in decimal form the LA output range data word. A means of varying the time delay to correspond to various ranges between 40 and 80 nautical miles in five calibrated increments is provided.

4.8.2.1 Electronics Unit

The EU, in addition to supplying power and control to the LA and R/T, also provides means for measuring and displaying the various LA outputs, indicating and identifying good status or malfunction.

4.8.2.2 Receiver/Transmitter

The R/T generates an optical return pulse with a controlled time delay from the LA output. The R/T return is initiated only if the LA output pulse is of sufficient power calculated to give a return from the lunar surface. The R/T also provides the expected background radiation levels for a check of LA receiver sensitivity.

4.8.3 Design Implementation

The GSE (see Figure 4-16) accurately verifies the measurement capabilities of the LA, determines if the laser pulse energy is above the critical threshold, and provides a direct readout of the LA status (that a fault exists or does not exist) on indicators located on the front panel.

4.8.3.1 Electronic Unit

The EU, shown in Figure 4-17 is a 29 inch long, 29 inch wide and 16 inch high assembly weighing 100 pounds. It provides the necessary power, control, measuring functions and displays for operating and indicating the output of the LA. The EU is housed in a Combination Case with a detachable cover, and can be located up to 45 feet away from the R/T when the LA is installed in the spacecraft.

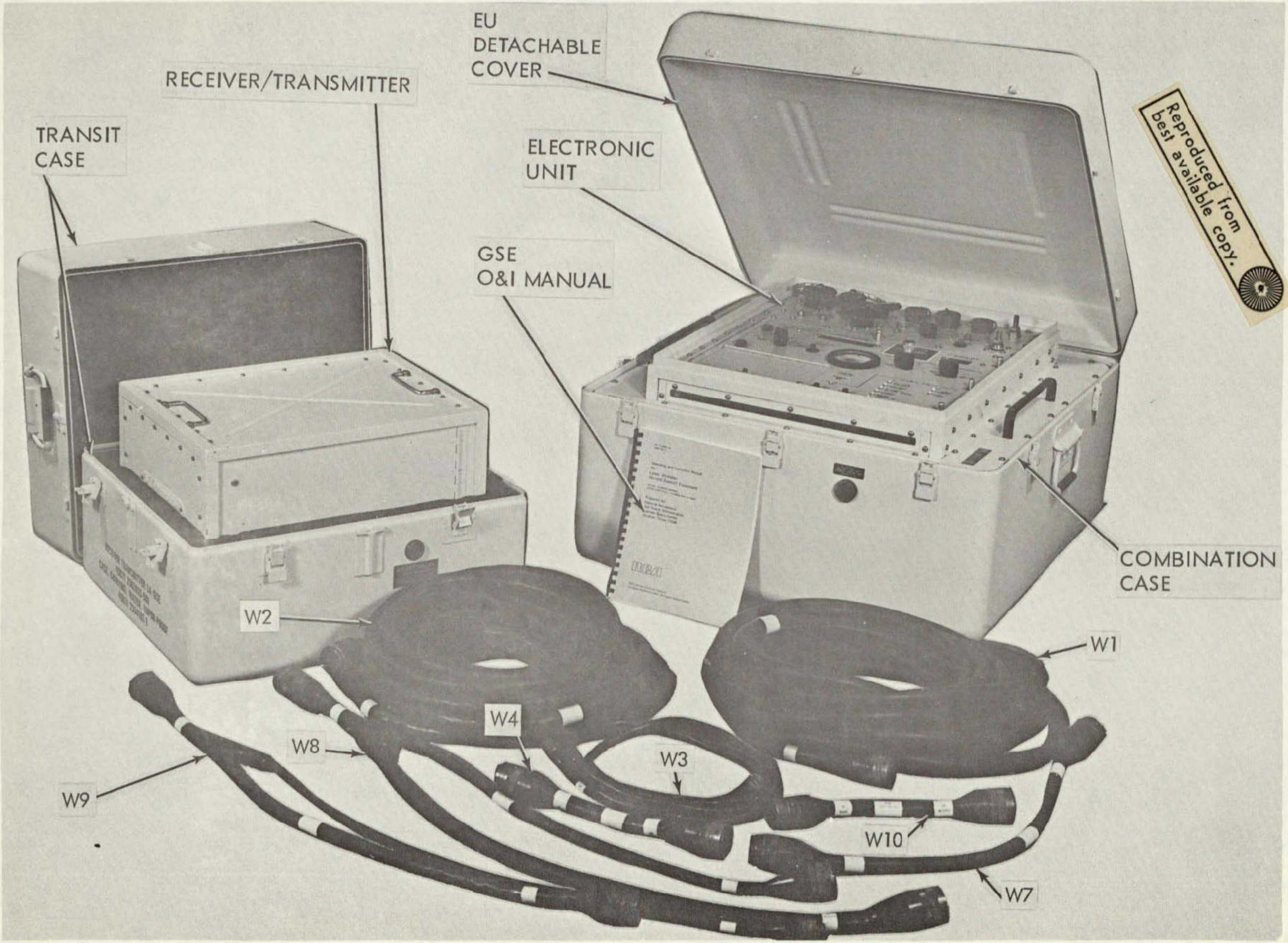


Figure 4-16. Laser Altimeter Ground Support Equipment

3.3.1 Control Panel

The front panel of this assembly, shown in figure 3-3, consists of two sections. The upper section is fixed and contains all connectors and power controls. The lower section contains all operating controls, indicators and readouts except for power and is hinged for easy access. The following discussion describes all front panel functions:

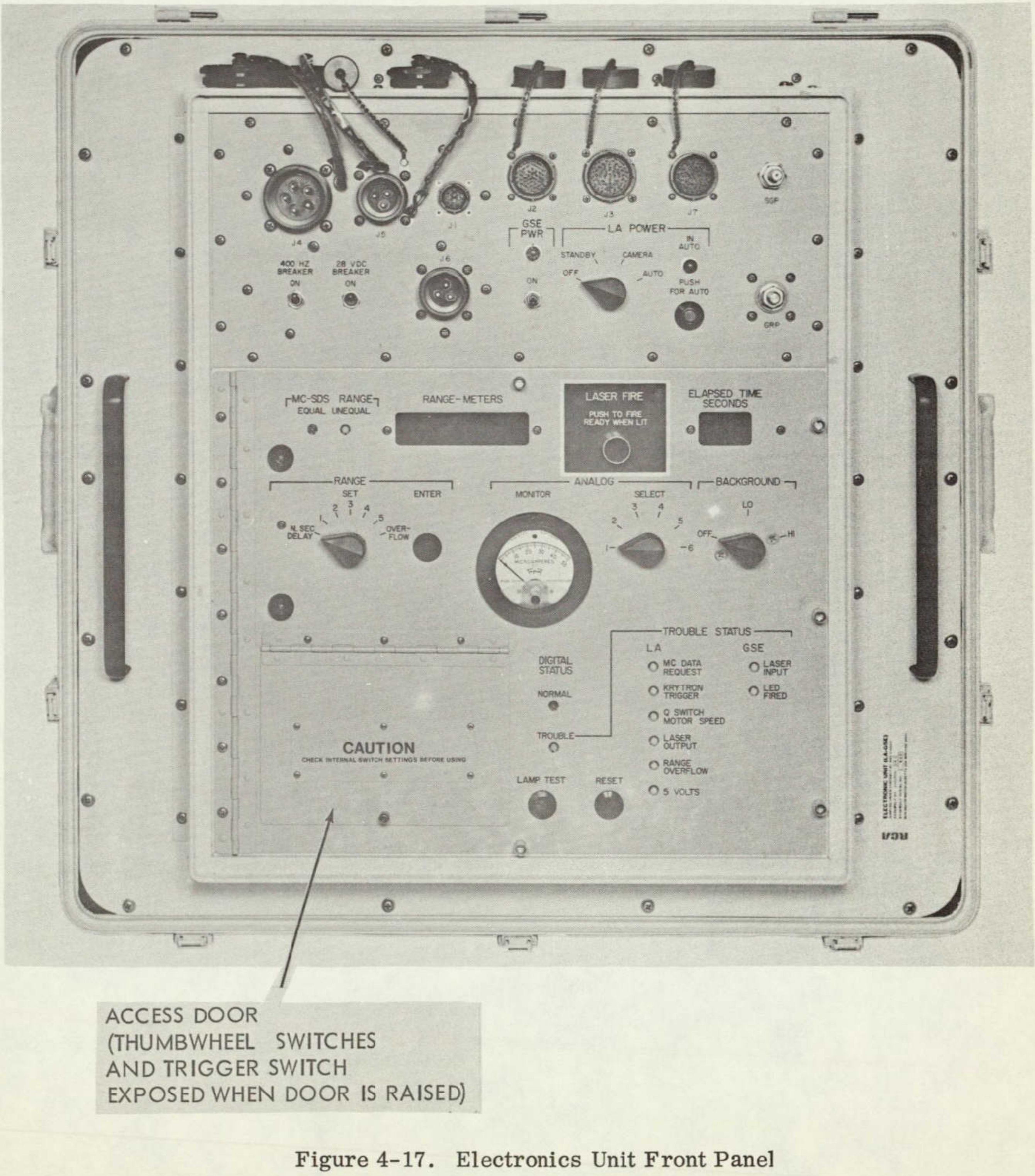


Figure 4-17. Electronics Unit Front Panel

The EU functioned as a remote-controller for the LA by supplying all necessary logic signals and power controls. It also provided power and control to the R/T which generates and receives the optical signals to and from the LA. Refer to Figure 4-18 for the following discussion. When the LA is being controlled by the GSE (i.e., all times except when the LA is in the spacecraft) the EU generates and supplies the following signals to the LA:

Pretrigger
Data Request
SDS Enable
Shift Clock
One PPS

These signals are of the proper amplitude, timing, and isolation necessary to simulate the Command Service Module (CSM) Mapping Camera (MC) commands for operating the LA.

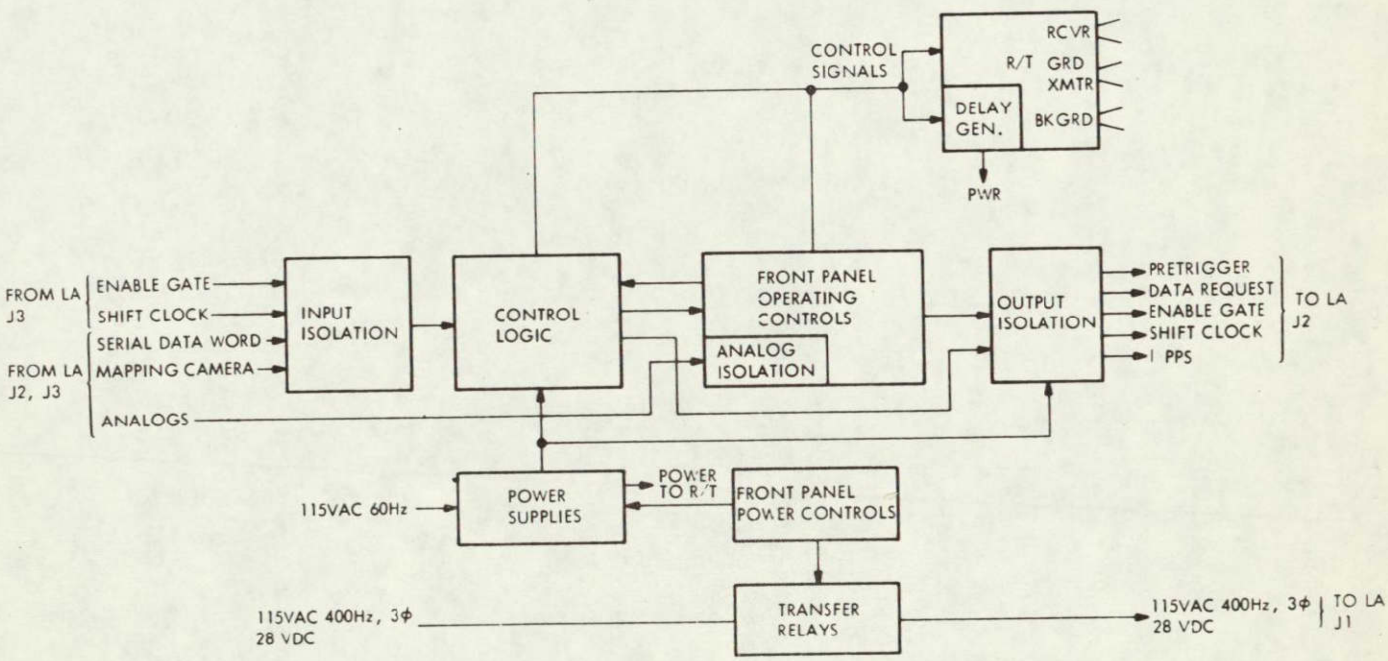


Figure 4-18. Electronic Unit Simplified Block Diagram

The EU also receives the LA outputs in the form of serial binary words and analog signals. The analog signals are displayed on a meter.

The serial words are clocked in and stored in registers. The altitude portion of the SDS word is converted and displayed on a six-digit decimal readout. The status bit portion of the word is fed to the LA TROUBLE STATUS lights. After storage, the MC altitude word is compared to the altitude portion of the SDS word and equality or inequality is indicated on the MC SDS RANGE EQUAL or UNEQUAL lights.

The EU contains all power supplies necessary to power the GSE. The input power for the LA, 28 VDC and 115 VAC, 400 Hz, 3Ø is controlled by the EU.

4.8.3.2 Receiver/Transmitter

The R/T shown in Figures 4-19 and 4-20, is a 19 inch long, 15 inch wide, and 13 inch high assembly which weighs 35 pounds. Housed in the R/T are a removable optics module and a delay generator module. Supplied with the R/T is a reusable transit case. Optical alignment is maintained by mating the boss surfaces of LA Telescope and Optics Module.

The LA laser output pulse of approximately 20 megawatts peak power and 13 nanoseconds width enters the receiver optics of the R/T and activates two photodetectors. The output of one photodetector is used for a minimum power input determination while the other output starts the delay generator. If the laser output power is above the preset minimum of 120 millijoules, the delay generator output gate is enabled for 2 milliseconds, permitting the delayed output pulse to trigger the light emitting diode (LED) driver. The output pulse can be delayed in one-nanosecond increments from 100 to 999, 999 nanoseconds. The delays of interest, when checking the LA, are from 0.4941 to 0.9882 milliseconds, corresponding to ranges of from 40 to 80 nautical miles.

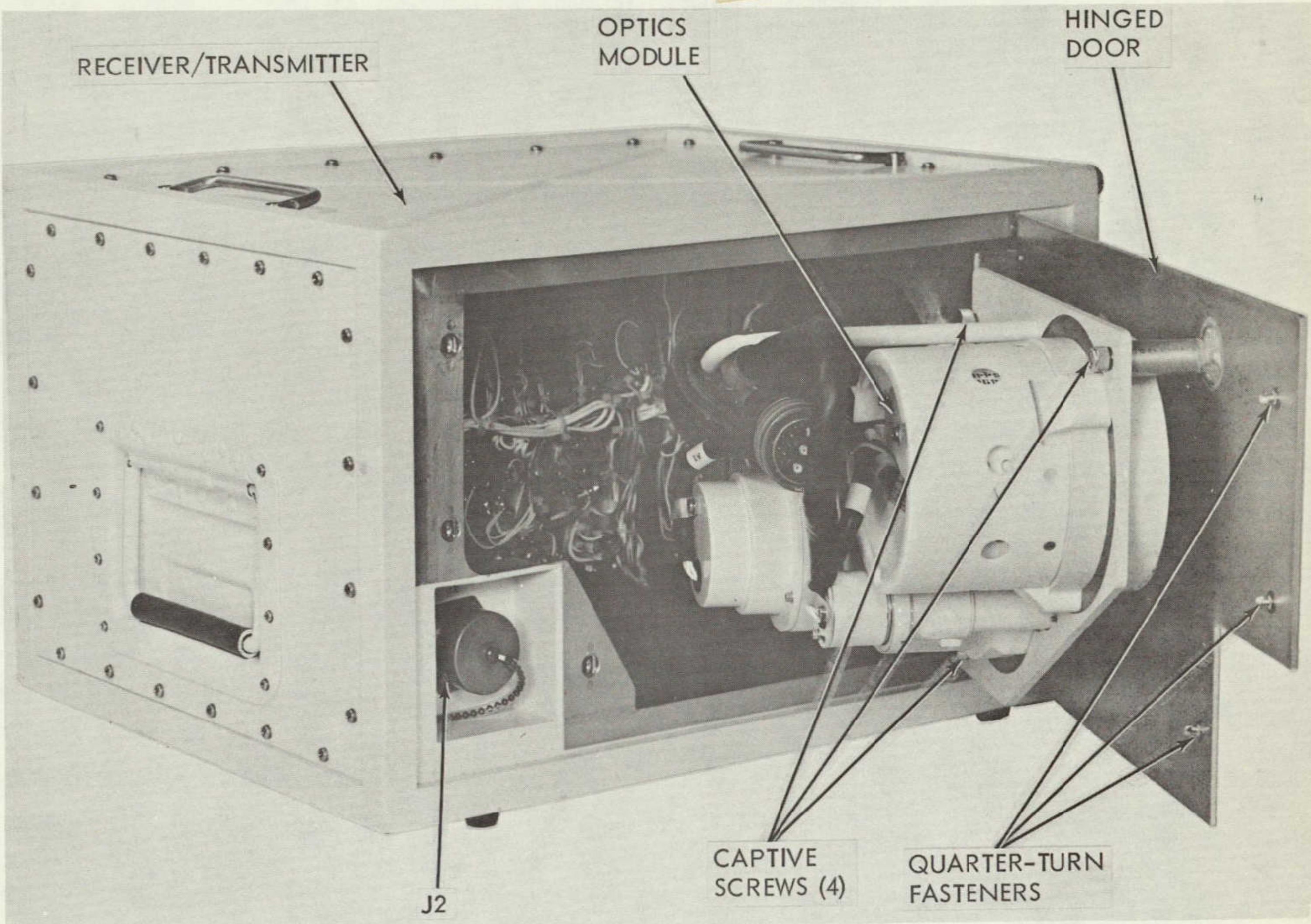


Figure 4-19. Receiver/Transmitter Assembly

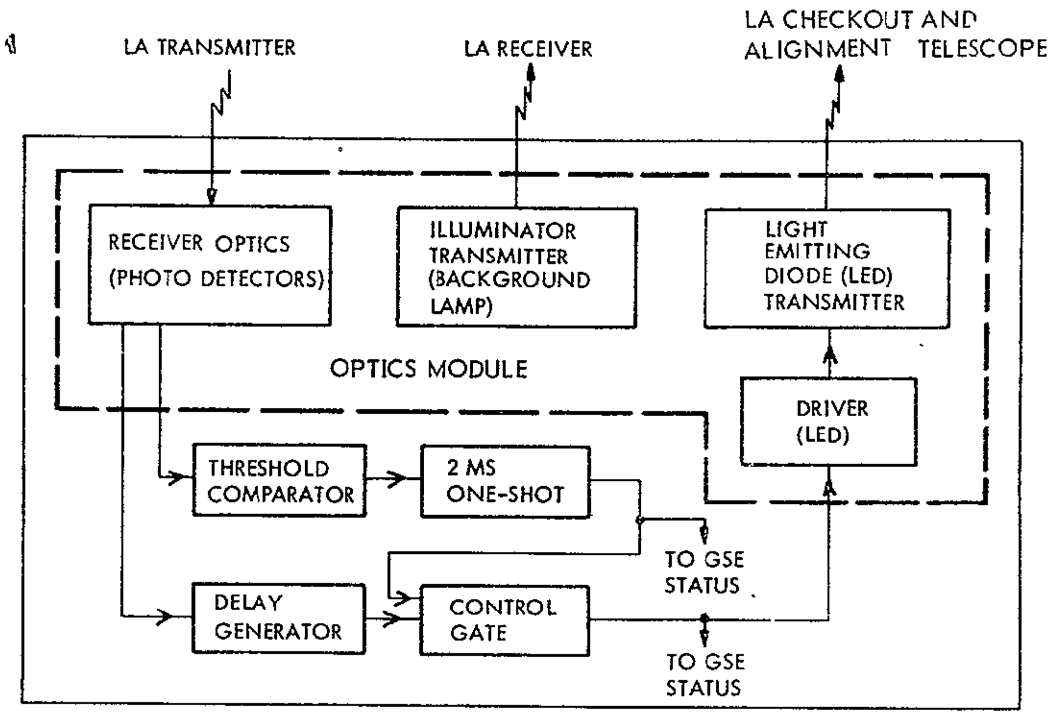


Figure 4-20. Receiver/Transmitter Block Diagram

The LED driver develops a 20 nanosecond pulse with a peak current capability of three amperes. (The peak current required by the LED is approximately 0.5 ampere.) The output of the LED is optically coupled to the LA receiver through the LA checkout and alignment telescope (CAT), which bypasses the field stop of the LA receiver optics.

The background light illuminates the LA receiver optics whenever range capabilities are being tested. The function of the background light is to simulate solar reflection received from the Lunar surface during LA operation. The receiver, LED transmitter and background lamp are contained in the removable Optics Module.

SECTION 5
TESTS AND TEST RESULTS

The acceptance and qualification tests of the GSE and LA are completely documented by the procedures listed in Paragraph 1.2.3.3 and by the data submitted in accordance with these procedures. Subassembly test procedures are included in the drawing description. Results of these tests are documented for each pertinent subassembly. This section therefore includes only highlights of certain formal tests and of special tests not formally documented.

5.1 DEVELOPMENT TESTS

5.1.1 Telescope High Reflectivity Mirror Coatings

Sample mirrors were coated having high reflectivity at 0.694 um. The coatings were tested by RCA for durability by exposing the coating to the output energy of a laser similar to that to be used in the Laser Altimeter. No diverging lens was used between laser and mirror; thus the energy levels were approximately six times higher than those expected in use. Neither visible damage nor loss of reflectivity occurred from the tests.

5.1.2 High Voltage Encapsulation Tests

Sample high voltage terminations were made using materials used on the LA to determine the adequacy of techniques for a vacuum environment. Silicone insulated wires were soldered to terminals, primed and coated with several light layers of GE RTV 566 silicone rubber. The terminations were well covered with a minimum of 0.06 inch thickness of RTV 566 and were essentially bubble-free. Only a few small bubbles in the 0.01 inch diameter size range were found on dissected samples. High voltage testing of samples between sea level pressure and 2×10^{-4} torr showed no arcing and no corona at voltages in excess of 10 KV.

Pull tests on insulated wire bonded by RTV 566 produced bond strengths between 50 and 60 psi which was more that adequate for the induced stress levels.

5.1.3 Special Photomultiplier Tube Tests

PMT acceptance test verified only ambient temperature parameters. Two flight tubes were subjected to a non-destructive Qualification Test at +55°C. All PMTs were further tested at RCA from +22°C to +55°C before installation into the LA's to verify noise spectrum data and prove compatibility with the video amplifier.

5.1.4 Video Amplifier Breadboard Tests

The video amplifier and AGC breadboard was tested for frequency response, propagation delay, and stability over the full 0 to +55°C temperature range. Data from all flight amplifiers plus the breadboard showed the propagation delay to fall between 11 and 13 nanoseconds under all conditions. The AGC control voltage is stable within 0.4 percent over temperature.

5.2 ACCEPTANCE TESTS

Each LA was subjected to an acceptance test prior to delivery. The acceptance test consisted of the following specific tests:

(1) Functional test
(2) Boresight test
(3) Laser energy test
(4) Receiver sensitivity test
(5) Prime power input test
(6) Vibration and alignment test
(7) Thermal vacuum test
(8) Power profile test
(9) Mechanical inspection

All LAs met all requirements of the above tests prior to acceptance. All failures during test were reported and analyzed.

Design changes as a result of test are reported in Paragraph 5.6.

5.3 SPECIAL TESTS

5.3.1 WSMR Tests

The prototype LA was tested to determine its ability to accurately range over near-operational distances. Although the LA is designed to operate over a 75 KM to 150 KM range in lunar orbit, a test range of 50 KM was used at WSMR. Atmospheric attenuation in 50 KM is greater than 10 dB and thus is equivalent to a lunar range of 150 KM.

Test run No. 6 provided the largest quantity of significant data. Correcting for the effect of the earth's atmosphere on the speed of light, the apparent target range was 50,264.8 M. The mean LA reading for the first 68 shots of test No. 6 was 50,263.6 M.

A very significant part of this test occurred when the LA pedestal was tilted upward, moving the beam from the target to the hill directly behind. Survey maps show that the increased ranges measured coincide with the profile of the hill. Considering the sloping terrain, lunar orbit range capability was projected to be 320 KM.

5.3.2 Laser Module Tests

Each Unit Test: Each laser module was carefully aligned and checked out prior to formal testing. The alignment and checkout required proper operation of timing, triggering and flash lamp circuits. It established efficiency, slope efficiency, power output and near field pattern of the laser output. Formal tests to verify the foregoing characteristics, the "start" pulse output and the setting of the status circuit threshold were performed on each module.

Each module was partially filled with helium, then a helium leak test was performed. The module was then purged and filled with high purity, dry nitrogen prior to installation in the Laser Altimeter.

Special Test: A number of special tests, life tests, triggering tests, tests of effect of temperature on laser output pulse and status threshold were conducted. Information obtained from these tests was used to predict or verify changes to improve module reliability. These included changes in Q-switch bearing type and lubrication, temperature compensation of laser status threshold circuit, and a change in flashlamp envelope material.

The tests demonstrated that the initial performance of the laser exceeded the design requirements by a significant margin; but that the rate of degration in performance was not directly predictable from preflight or life testing.

5.3.3 2TV2

The prototype LA was subjected to the 2TV2 test early in March 1971 at MSC Houston. Due to schedule limitations, the prototype LA was not operating to specification in that the Laser Output power was low. MSC was cognizant of degraded prototype performance before the test.

RCA received no written report detailing the results of the test, but did receive data which indicated some malfunctions. Information was also received that

(1) The 3 Ø 400 Hz fuses had blown in the SIM
(2) The LA had been turned on at pressures between 650 and 10^{-3} torr

Upon inspection and retest of the LA, RCA could find no reason for the LA to cause the fuses to blow. There was, however, evidence of a high voltage breakdown which was probably caused by LA turn-on at near-critical pressure.

5.3.4 Shock Test

5.3.4.1 CSM/SLA Shock

The LA was subjected to the CSM/SLA Pyrotechnic Separation Shock Test having a spectral distribution as shown in Para. 2.3.2.3.1 (i). The LA experienced no electrical, optical or mechanical degradation as a result of this test. The test data and results are delineated in the Qual Test Report.

5.3.4.2 SIM Door Jettison Shock Test

This test was not performed because the specified levels (3,000 g) was greater than the test equipment capability. However, subsequent test data from the 2TV2 test indicated peak flight inputs to the LA of approximately 300 g which are lower than the CSM/SLA levels to which the LA was tested.

5.3.4.3 EMI Tests

The conducted and radiated interference data obtained during the GSE EMI investigation is considered adequate to be used to evaluate the LA/GSE's potential effects on the operation of neighboring electronic equipments. As all of the radiated interference levels measured appeared to have been emanating from the LA/GSE Electronics Unit, the impact of these radiated interference levels on the operation of electronic equipments within the SIM Bay (as well as equipments outside of SIM) should be negligible for two reasons:

(1) The LA/GSE EUs potential physical separation distance of 45 feet from the LA/GSE Receiver/Transmitter Unit (which directly connects to the Laser Altimeter) and

(2) The EUs inherent portability.

These two facts provide both shielding and separation capability - the basis for proper isolation of noise source and affected equipment(s).

5.4 QUALIFICATION TEST

The LA was subjected to Qualification Tests in order to demonstrate compliance with the requirements delineated in Para. 3.2.3. The LA successfully met the requirements. The test specification, the test procedures, the test data and results are delineated in the Qualification Test Report. Figure 5-1 shows the LA set-up for Y-axis vibration testing, and in Figure 5-2 the LA is mounted in the lunar shroud preparatory to orbital simulation solar-vacuum testing.

5.5 CHANGES RESULTING FROM TESTS

The following design changes were incorporated in all flight LA's.

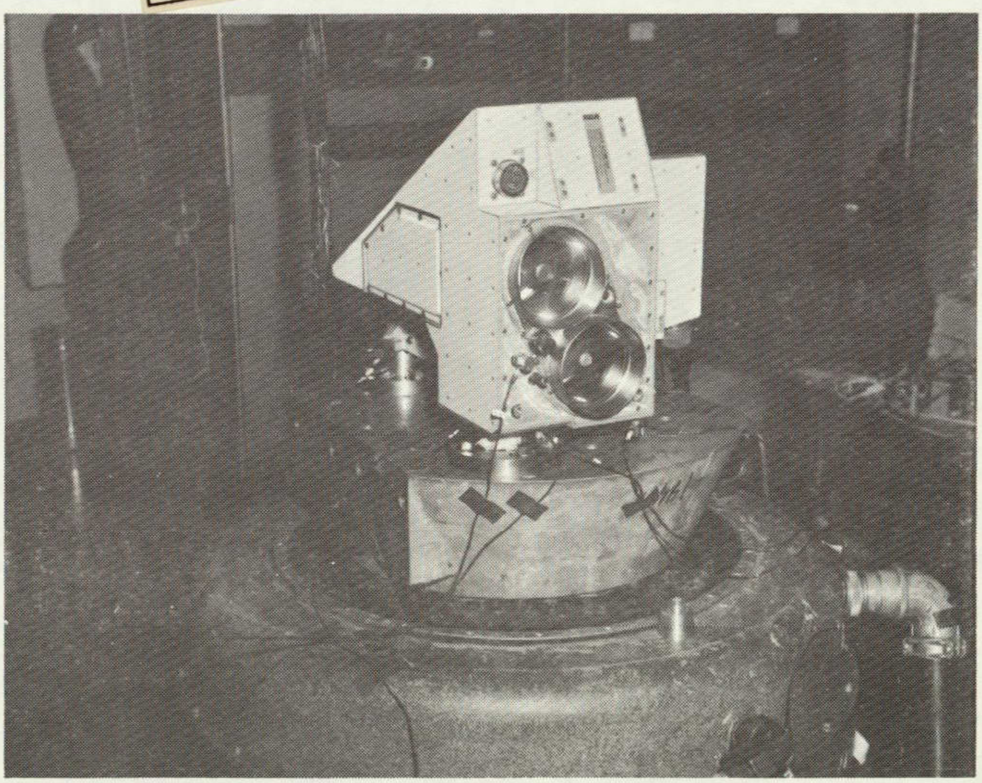


Figure 5-1. Vibration Test Setup (Y-Axis)

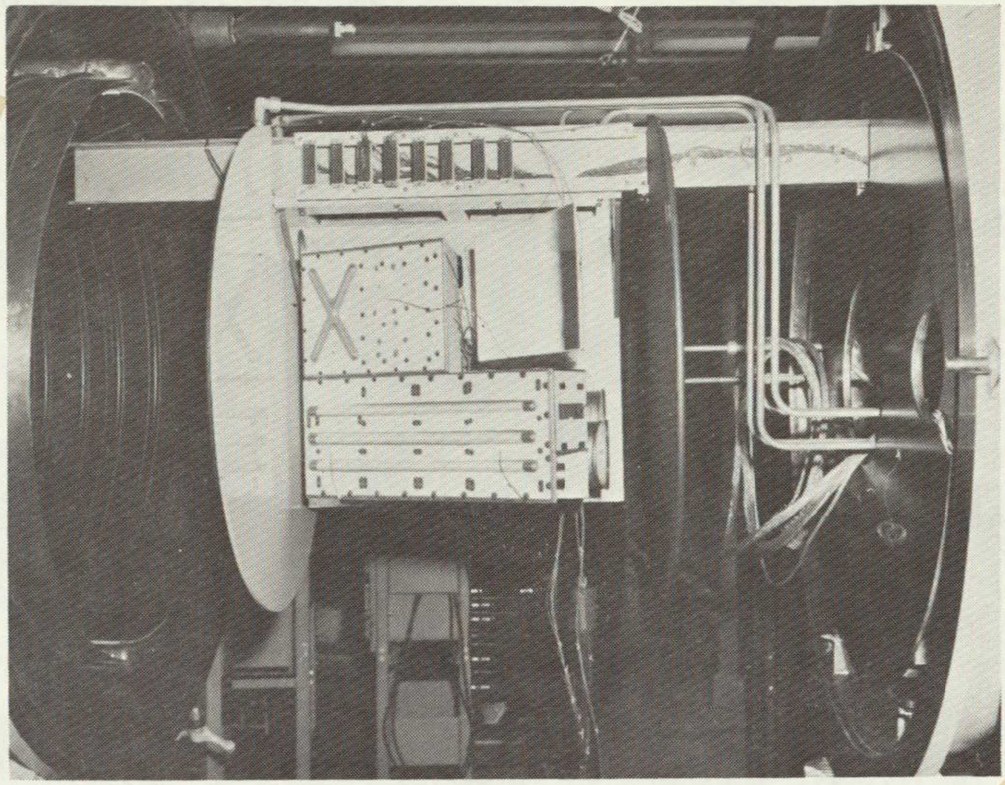


Figure 5-2. Low Pressure Solar Energy Setup

5.5.1 Laser Module

Fill and Check Valve: The swaged copper tubing pressure seal was changed to a standard air valve to facilitate access to the module interior in the assembly and pretest process and periodic pressure checks to assure adequate sealing.

Wiring: The original P.V.C. insulated high voltage wire was replaced with silicone insulated wire to eliminate outgassing.

Cleanliness: All laser modules finally assembled and purged in a laminar air flow clean bench in an isolated area.

5.5.2 Electronics

Relatively few changes were made to the LA electronics as a result of specific tests. Temperature testing resulted in a LVPS oscillator drive design change to provide reliable operation at low temperatures. Also, a divider was added to the 5 volt analog signal to meet the specified upper limit of 5 volts.

5.5.3 Mechanical

The Qual Level Vibration Test indicated that the design contained two minor deficiencies:

(1) The EMI screen was found to have been torn after Qual Level Vibration in the first axis.

(2) Two of the four mounting screws of the Energy Storage Capacitor were found to have completely backed out, the other two screws loosened after completion of the three axes of Qual Level Vibration.

5.5.3.1 EMI Screen

The EMI screen mounts to the telescope and to the sheet metal shear webs of the main structure. The screen provides EMI shielding and allows the LA to exhaust rapidly at altitude.

The design intent was to have negligibly small mechanical coupling between the main structure and the telescope through the screen so that relative motions of the sheet metal would not be transferred to the telescope.

However, the initially selected screen material (1/32 thick expanded metal) proved to be so stiff that relative motion of the sheet metal and the telescope assembly resulting in tearing of the screen.

The problem was solved by changing the screen material to a stainless steel, 200 mesh screen of 0.0016 dia. wire. This material provided proper strain relief and minimized transmission of force by the screen.

5.5.3.2 Energy Storage Capacitor Mounting Screws

The screws were found to have backed out of the self-locking inserts. The inserts exhibited no locking capability after the test. It was impossible to separate cause and effect after the fact (i.e., whether improper insert installation caused the backing out of the screws or insufficient preload torque caused the screw to back out and then to destroy the insert locks). To increase the safety margin, albeit the original design was presumed to have been adequate, higher strength screws were specified which allowed for a preload torque more than twice the previous design (45 lb-in vs. the previous 20 lb-in). Retest proved the adequacy of the revised mounting screws and torque.

5.5.4 Telescope

During the system testing of the Prototype Laser Altimeter, light leaks in the telescope allowed indirect coupling of the laser output into the photomultiplier tube (PMT). The leaks caused PMT saturation which prevented normal detection of the return pulse in the receiver. The problem was solved by adding a focusing lens and a secondary glare limiting field stop between the narrow bandpass filter and the PMT. The glare stop limited the field-of-view within the telescope that the PMT could "see" and eliminated detectable laser pulse noise. The added focusing lens was anti-reflection coated, peaked at 6943Å, so that it attenuated received energy by only a fraction of one percent.

All flight telescopes were designed to incorporate this and several other minor changes. The diverger lens holder and field stop holder tubes were changed from Cervit to Invar, vent holes in the transmitter and receiver telescopes were oriented away from each other, several light baffles were added, and certain areas were painted black to minimize reflections. The glare stop alone was sufficient to solve problem in the Prototype telescope. The problem was not encountered in any subsequent system (flight and qual.).

5.6 FAILURE ANALYSIS AND CORRECTIVE ACTION

All reportable failures resulting from tests of prototype, flight and qualification LA's were submitted by the RCA Reliability engineer to MSC. Fifty-six Failure Investigation Action Reports (FIAR's) were submitted. In each case the failure was investigated by RCA, the cause or source of the failure was identified and corrective action was taken.

The reported failures occurred during formal testing or subsequent troubleshooting. Excluding the Laser Module, which had the most severe combination of constraints and operating conditions, the general failure causes were as follows:

Operator or workmanship (RCA)	15
Test Equip. & Procedures	10
Vendor/Subcontractor Material & Parts	7
Design (RCA)	6
Acceptable Out-of-spec Condition	2

Laser Module failures were associated with:

Output Degradation	5
Optical Alignment	5
Pressure Leakage	2
Triggering	2
Status Circuit	2

The triggering problems were a result of deficiency in vendor application data but were corrected. The status circuit problems were caused by an electrical design deficiency which was corrected and by a design change which required more precision from the sensor than its original design contemplated.

The pressure leakage resulted from workmanship deficiencies which were corrected.

The optical alignment failures were caused by a processing deficiency in the qual laser module and by a marginal design of the resonant reflector screw assembly, which was corrected.

The output degradation failures were attributed to a number of causes; processing, workmanship, vendor parts and design contributed in about the same ratios as for the remainder of the LA.

5.7 TEST SAFETY

Safety hazards from LA operation could arise only during ground test or troubleshooting. The principal hazard was from the high intensity laser light output. The level was such that eye damage could be caused by viewing the beam directly or specularly reflected.

During in-plant testing when laser energy or beamspread was being measured a number of mandatory safety precuations were invoked. For all other testing at all test locations either the lens caps or the GSE optical coupler were required to be covering the LA telescope apertures. There were no incidents during the program.

The only high voltage hazard in LA testing would require the LA doors to be opened, the door interlocks to be closed, the high voltage potting to be defective and prime 28V power to be applied to the LA. This condition could only be encountered at the manufacturer's plant; therefore, manufacturer's personnel were duly indoctrinated. There were no incidents during the program.

SECTION 6

RECOMMENDATIONS

In the event that Laser Altimeters having similar performance requirements are needed in the future the following changes are recommended for consideration:

(1) Telescope

(a) Provide for mechanical disassembly for repair or modification, even at the expense of increased weight.

(b) Provide a conical light baffle around the receiver field stop to exclude off-axis radiation.

(c) Eliminate checkout telescope and provide for internal illumination of field stop, if necessary.

(2) Laser Module

(a) Remove all signal processing circuits except trigger circuit from module.

(b) Decrease Kryton keep-alive current by factor of two.

(c) Stiffen bottom surface of module housing.

(d) Remove laser output status sensor from module and use external beam splitter and sensor.

(3) High Voltage Supplies

Modify layout to increase clearances and facilitate RTV application.

(4) Mechanical

(a) Install a bushing in the main casting to accept the MC mounting interface locating pin.

(b) Use spline socket head screws rather than hex socket wherever frequent removal and installation are required.

(5) PFN Controller

Increase the resolution of the servo voltage control and implement both high and low output thresholds, with the normal operating region the dead zone between thresholds.

SECTION 7

IDENTIFICATION OF TECHNICAL PERSONNEL

A complete list of all RCA engineers who made technical contributions to the Laser Altimeter or GSE design could not be prepared without inadvertent omissions. Those listed below had major responsibilities in the program.

Electrical Design

D. Dion, RCA ASD

J. J. Klein

Z. Legedza

K. Miller

J. F. Salemme

R. G. Spiecker

Mechanical Design

N. Meliones

M. Neiman

F. Pratt

Optical Design

R.C. Guyer

C.B. Park

Laser Design

W.S. Byk

T.M. Nolan

R.A. Tuft

Technical Direction/Prog. Mgmt.

M. Burmeister

J.H. Woodward

Thermal Design

D. Morand

M. Weiss, RCA MSRD

GLOSSARY

AGC	-	Automatic Gain Control
BTE	-	Bench Test Equipment
CAT	-	Checkout and Alignment Telescope
CDR	-	Critical Design Review
CSM	-	Command and Service Module
ECP	-	Engineering Change Proposal
EMI	-	Electromagnetic Interference
EU	-	Electronic Unit
EVA	-	Extra Vehicular Activity
FAR	-	False Alarm Rate
FIAR	-	Failure Investigation Action Report
FOV	-	Field of View
FSDS	-	Fairchild Camera & Instrument Co., Space & Defense Systems
GSE	-	Ground Support Equipment
ICD	-	Interface Control Document
KSC	-	Kennedy Space Cneter
LA	-	Laser Altimeter
LED	-	Light Emitting Diode
LM	-	Lunar Module
LSB	-	Least Significant Bit
MC	-	Mapping Camera
MSB	-	Most Significant Bit
MSC	-	Manned Spaceflight Center
N/R	-	North American/Rockwell, Space Division
PDR	-	Preliminary Design Review
PFN	-	Pulse Forming Network
P&I	-	Performance and Interface
PMPS	-	Photomultiplier Power Supply
PMT	-	Photomultiplier Tube

RASPO	-	Resident Apollo Spacecraft Program Office
RCS	-	Reaction Control System
R/T	-	Receiver/Transmitter
SDS	-	Scientific Data System
SIM	-	Scientific Instrument Module
SLA	-	Service Module LM Adapter
SM	-	Service Module
TAM	-	Thermal Analytical Model
WSMR	-	White Sands Missile Range