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DISCLAIMER

HiRes Camera and LIDAR Ranging System for the *Clementine* Mission

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ABSTRACT

Lawrence Livermore National Laboratory developed a space-qualified High Resolution (HiRes) imaging LIDAR (LIght Detection And Ranging) system for use on the DoD Clementine mission. The Clementine mission provided more than 1.7 million images of the moon, earth, and stars, including the first ever complete systematic surface mapping of the moon from the ultra-violet to near-infrared spectral regions. This article describes the Clementine HiRes/LIDAR system, discusses design goals and preliminary estimates of on-orbit performance, and summarizes lessons learned in building and using the sensor. The LIDAR receiver system consists of a High Resolution (HiRes) imaging channel which incorporates an intensified multi-spectral visible camera combined with a Laser ranging channel which uses an avalanche photo-diode for laser pulse detection and timing. The receiver was bore sighted to a light-weight McDonnell-Douglas diode-pumped Nd:YAG laser transmitter that emmitted 1.06 μm wavelength pulses of 200 mJ/pulse and 10 ns pulse-width. The LIDAR receiver uses a common F/9.5 Cassegrain telescope assembly. The optical path of the telescope is split using a color-separating beamsplitter. The imaging channel incorporates a filter wheel assembly which spectrally selects the light which is imaged onto a custom 12 mm gated image intensifier fiber-optically-coupled into a 384 x 276 pixel frame transfer CCD FPA. The image intensifier was spectrally sensitive over the 0.4 to 0.8 μm wavelength region. The six-position filter wheel contained 4 narrow spectral filters, one broadband and one blocking filter. At periselene (400 km) the HiRes/LIDAR imaged a 2.8 km swath width at 20-meter resolution. The LIDAR function detected differential signal return with a 40-meter range accuracy, with a maximum range capability of 640 km, limited by the bit counter in the range return counting clock. The Imagery from the HiRes is most useful for smaller scale topography studies, while the LIDAR data is used for global terrain and inferred gravity maps.

Keywords: Clementine, LIDAR, Nd:YAG Laser, Lunar Imagery, Lunar Topography, Image Intensifiers, Imaging Sensor

INTRODUCTION

The Clementine LIDAR unit is a modification of an earlier active sensor developed for the Brilliant Pebbles program an advanced spacebased interceptor development program sponsored by the Ballistic Missile Defense Organization (BMDO), formerly the Strategic Defense Initiative Organization (SDIO). The HiRes/LIDAR system incorporates an imaging channel consiting of an image intensified CCD camera and a ranging channel that uses an avalanche photodiode (APD) to detect and time signal returns. These channels share a common collection aperture telescope and are bore sighted to light-weight McDonnell-Douglas diode-pumped Nd:YAG laser transmitter. The light-weight beryllium telescope, the 6-position filter wheel, the camera focal plane and electronics, the gated intensifier, and the APD detection circuitry were taken from the earlier interceptor development program. Specfic filter bandpasses, the range resolution and maximum range of the return electronics, and the laser output divergence were modified for the Clementine mission. Four spectral bands were selected to provide spectral mapping of selected lunar target sites, while one place was saved for a solar-protection opaque filter and one was reserved for a broadband filter. Optics image quality and sun shield angle were designed for optimal performance during the asteroid geographos encounter. The sensor incorporated radiation resistant materials and design practices to meet the goal of survival through long space flight missions.

In addition to generating a data set for lunar mapping, the HiRes/LIDAR system has provided data for sensor lifetime performance on a space platform and provided valuable design lessons for future projects. The remainder of the paper summarizes the Clementine mission and goals, describes the LIDAR's construction, operation and testing, and presents some operational results and conclusions.

CLEMENTINE MISSION

Mission Goals

The primary objective of the Clementine Program was to demonstrate certain aspects of lightsat technology of interest to the Ballistic Missile Defense Organization (BMDO), including the space qualification of a suite of 6 light-weight, low power imagers [Refs 1, 2, 3 and 4] for future Department of Defense flights. A secondary objective was to produce data of interest to the scientific community. Science missions centered on mineralogical mapping with 100% coverage of the lunar surface (which was successfully completed), and spectral studies of the near-Earth asteroid Geographos (which was not completed). Studies of radiation environment effects, camera noise under spacecraft platform control, and all lifetime issues were also performed.

Mission Synopsis

The Clementine spacecraft launched on schedule on January 25, 1994 from Vandenberg Air Force Base (CA). After 25 days in lunar transit, which included a week in low earth orbit and the remainder in phasing loops, the spacecraft was inserted into an elliptical polar lunar orbit where it successfully spent 71 days performing a systematic mapping of the Moon. The spacecraft left the Moon on May 4, 1994 and was in the middle of a pair of orbital loops around the Earth preparatory to obtaining a gravity-assist boost from the Moon towards Geographos when a software failure caused complete loss of attitude control system propellant and put the spacecraft in an 81-rpm spin. The spacecraft could not be despun to a low enough rate to permit further acquisition of resolvable images, nor could the spacecraft be pointed to a specified direction. As a result there was no possibility of completing the Geographos phase of the mission. Refs [5, 6] provide good overviews and insight into utility of the Clementine data that have been analyzed.

HiRes/LIDAR MISSION GOALS

The primary purpose of the Clementine mission was to flight qualify and test the state-of-the-art sensor payload for DOD applications. A secondary objective was to produce data of interest to the scientific community. DOD goals included in-flight performance of the sensors and lifetime reliability in a long-duration space environment flight. The HiRes was succesfully used for studies of of radiation environment effects, camera noise, and spacecraft platform stability studies.

The science mission centered on minerological mapping of 100% of the lunar surface in 11 spectral bands, using the UV/Visible and Near-IR cameras in the sensor suite. The HiRes imager, providing 4 spectral bands and a broadband filter, gathered high-resolution spectral mapping data in bands similar to the UV/Visible at selected lunar sites. Broadband data was gathered along sections of each orbit near the poles for morphology studies. The HiRes had been scheduled for use in detection/navigation during the asteroid rendesvous. LIDAR ranging information was obtained for all nadir-looking mapping orbits at spacecraft altitudes less than 640 km.

HiRes/LIDAR DESCRIPTION

Figure 1 shows a photograph of the assembled HiRes/LIDAR Receiver unit and Figure 2 shows a cross sectional drawing of this assembly. The unit consists of an optical system (telescope assembly and light baffle), a beamsplitter, an APD detector module, a filter wheel module, an image intensifier module, a camera module, and a system controller module, each of which is discussed below. Table 1 summarizes the camera's technical specifications. Figure 3 shows a functional block diagram of the HiRes/LIDAR system.

Figure 1. Clementine HiRes/LIDAR receiver system.

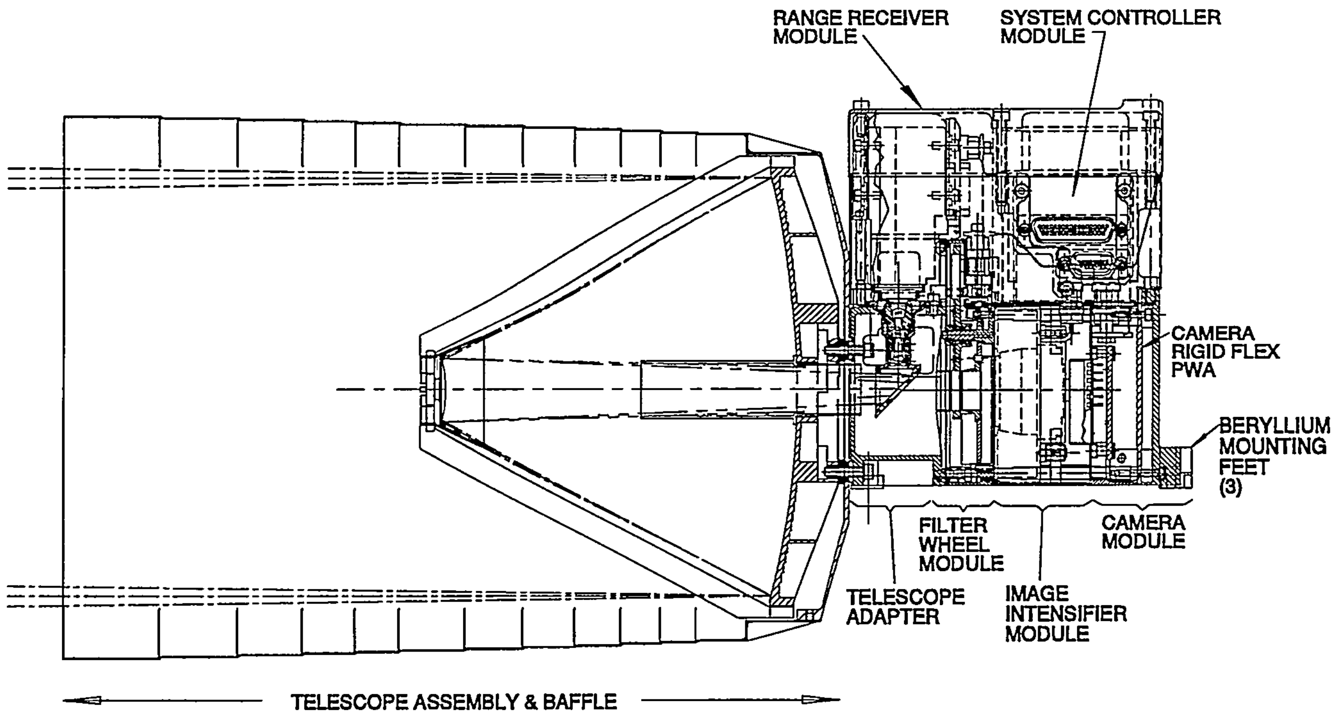


Figure 2. Cross-sectional drawing of the Clementine HiRes/LIDAR receiver.

Table 1. HiRes/LIDAR receiver system performance spacifications.

Attribute	Imaging Channel	Ranging Channel
Detector		
Type	Thomson TH7863 Si CCD; Litton XT0221 image intensifier tube (S20/P20), 12mm dia.	Si APD C30954E, 0.4 to 1.1 μm
Pixel format	384 x 288	Single
Pixel size	23 x 23 microns	0.5 mm^2
Optics		
Type	Cassegrain telescope	Shared Cassegrain telescope with beam splitter and reimaging lens for APD
Clear aperture	131 mm	
Speed	F/9.5	
Imaging		
Wavelength	0.4 to 0.8 μm	1.064 μm
Field of view	0.4° x 0.3°	1 mrad dia
Pixel IFOV	18 μrad	1 mrad dia
Point spread	50 μrad	N/A
Clementine filters	415 nm cw (± 20 nm bw), 560 (±5), 650 (±5),750 (±10), 400 to 800 broadband	N/A
Camera Electronics		
Type	Thomson controller, programmable gain	40 meter range resolution with programmable threshold (8 bits)
A/D resolution	8 bits	-
Frame rate	10 Hz	8 Hz
Readout time	27.4 ms	-
Integration time	0.01 to 100 ms	-
Gain	150, 350, 1000 electrons/count	APD gain 100x, Amplifier gain 200x
Offset control	248 gray levels	-
Power	9.0 W (imaging only)	9.5 W (imaging + ranging)
Filter Wheel System		
Type	6 position, 90° stepper motor driven, Hall effect position sensors,	
Step and settle time	≤ 250 ms	
Postion repeatability	≤ 10 mr	
Power	0.15 W quiescent, 11.0 W stepping	
Physical/Thermal		
Mass	1120 grams	
Envelope	17.0 cm x 18.1 cm x 36.4 cm long	
Temperature Range		
Operating	-20° to 30°C	
Non-operating	-35° to 50°C	

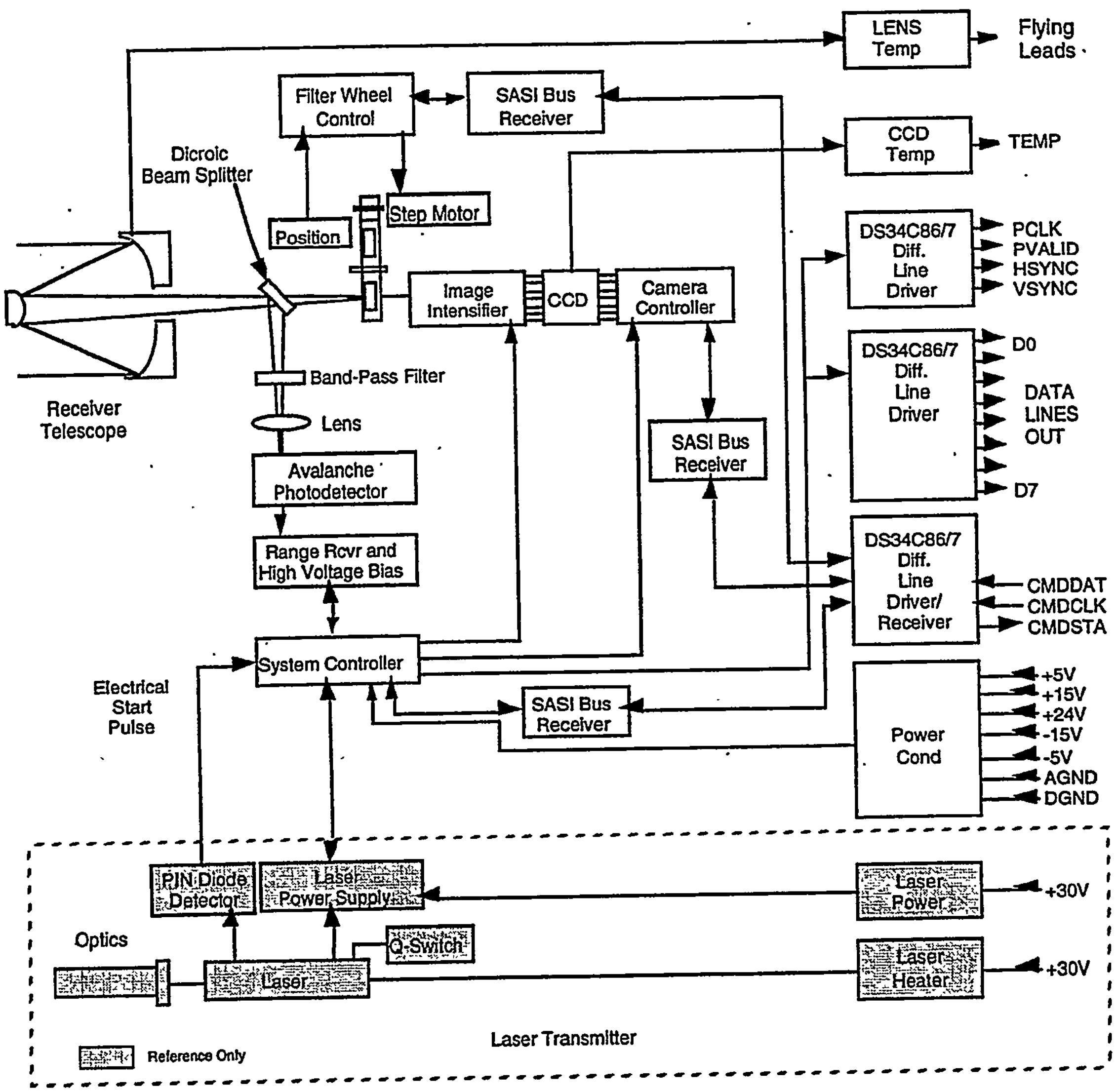


Figure 3. Functional block diagram for the Clementine HiRes/LIDAR system.

HiRes/LIDAR Receiver Construction

The HiRes/LIDAR receiver was designed as a modular system. Each major element was built as an interchangeable module which stacked up into a complete assembly. The unit was designed to survive a 19.8 g rms, 60 second duration launch aboard a Titan II G vehicle, and operate in space for the original seven month duration Clementine mission.

Receiver Optical System

The HiRes/LIDAR shares a common collection telescope, using a dichroic beam splitter to transmit wavelengths <0.9 µm towards the image intensifier/CCD imager while reflecting the 1.06 µm laser pulse return to a spectrally filtered avalanche photodiode (APD) detector.

The small field of view inherent in the imaging path, due to the requirement for high resolution and the limited number of pixels in the focal plane array, allows high-quality imagery from a Ritchey-Cretien 2-mirror system with no added field correction optics. The filter wheel location is balanced: close to the focal plane to minimize required filter and wheel sizes, but not too close to minimize the localized obscurations that could be caused by debris settling on the optical surface. The telescope structure is made of beryllium, chosen for lightweight considerations. The primary/secondary/strut weight of the 131 mm aperture diameter primary is less than 140 g and still allowed as-manufactured wavefront errors less than 1-wave He-Ne p-v, the wavefront goal to minimize optical aberrations in comparison to the image intensifier blurring. Shuttering is accomplished by gating the voltage across the microchannel plate in the image intensifier.

The LIDAR ranger re-images the primary entrance aperture onto a pupil plane at the APD detector surface. A field stop is located at the intermediate image. The laser output is collimated to a 0.5 mrad output beam, limiting beam footprint diameter to less than 250 meters at the lunar surface. Limiting the footprint helps to ensure that the return beam is detected within the same time bin in the case of rugged ground terrain. The 0.5 mrad divergence is a compromise between better beam collimation and laser output telescope dimensions, which were 3-cm diameter in the flight unit. The acceptance field stop is set at 1 mrad, diameter, allowing a 0.25 mrad (radial) beam wander without clipping return signal.

Filters in the imaging camera provide better than 10^{-3} out of band rejection. Rejection limits the out of band integrated signal to less than 1% of the in-band signal over typical scene spectral radiance distributions. The filter for the LIDAR ranger is a narrow band spectral filter, designed to reduce the scene background light. The mission profile was to fly an elliptical orbit around the moon, with periselene at 30° N/ 30° S in the two months of lunar mapping, closest to the moon during "day" lighting conditions. Ranging thus was possible only against a bright background, requiring filtering for proper operation.

Environmental design efforts included the common beryllium telescope design, potting of relay lenses into aluminum cells, and flexures between the beryllium telescope structure and any aluminum hardware to avoid thermal-stress deformation when the telescope temperature fluctuates.

Receiver Baffles/Stray Light

Stray light control included an external baffle for large-angle exclusion and two internal telescope baffles to block near-field light from a direct path to the focal plane. The external baffle is extended far enough to provide a 40° solar exclusion angle before light impinges on the secondary mirror or other internal surfaces directly viewable from the FPA location. This angle was based on the projected angle between the sun and Clementine during the Geographos encounter.

HiRes usage during the lunar mapping portion of the Clementine mission was imaging of bright scenes. In this portion of the mission, veiling glare, rather than solar rejection at a specfic angle, is used to quantify the merit of the stray light rejection. In-flight data will be used to estimate the veiling glare contribution as a function of viewing angle.

Surface finishes on the HiRes baffle surfaces were black anodize for the internal baffles, where handing is a concern, and a MIL-F-495 Cu-etch process on the external baffle. This process creates a porous, non-particulating, non-outgassing structure and exhibits reflectance properties equivalent to Ball and Martin blacks.

Image Intensifier Module

The image intenisifier used in this system (XT0221) is a new 12-mm active area device manufactured by Litton with a custom gating power supply, developed by General Atomics. The spatial resolution of the miniaturized image intensifier is aproximately 35-40 lp/mm. The complete assembly packages into a compact form factor that was designed to mechanically interface to the other modules of the HiRes/LIDAR assembly. Image shuttering is accomplished through a reverse bias voltage gating between the photocathode and the front surface of the microchannel plate. Maximum integration time is 773 milliseconds in 10.67 microsecond increments. Spectral response is limited in the system by the S-20 photocathode to lie between 0.4 and 0.8 µm. Images of the day side of the moon used intensifier gate times on the order of 1 millisecond with relatively low gain settings. Lifetime concerns of the photocathode and micro-channel plates in the intensifier unit drove operational settings to low exposures. This resulted in photon shot noise contributing significantly to the overall noise in the HiRes sensor.

Camera Electronics

The camera module (Ref. [1]) is the chassis and core electronic unit of this camera. It is also the basic building block of the Clementine star tracker and Clementine HiRes cameras. It contains the CCD (Thomson TH7863) and controlling circuitry on a flexible printed wiring assembly (PWA) which communicates via a Synchronous Addressable Serial Interface (SASI) bus protocol to the sensor processor.

The electronics are designed around the CCD, a CCD controller (Thomson TH7990), and an Actel FPGA. The camera sends and receives commands from the Clementine Sensor Imaging Processor (SIP) via a differential line driver/receiver. A SASI receiver interprets all commands. The Actel FPGA then processes all commands, generates video timing, and controls operation of the TH7990, which in turn controls the CCD. The FPGA also controls the analog circuits for Gain, Offset and Double Correlated Sampling (DCS). After decoding each SASI command, the camera returns a status word, and after capturing an image, the camera returns digitized video to the SIP. This process is represented functionally in Fig. 4.

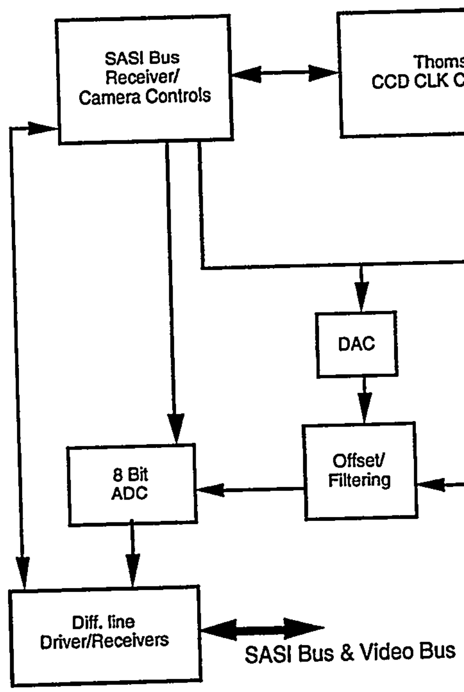


Figure 4. Actel camera electronics functional block diagram.

In the analog domain, the output of the CCD is buffered through a low-gain emitter-follower amplifier before global gain is applied. The camera has three gain settings (Table 1). Camera gain is selected by setting one of the gain control bits HI which switches a gain resistor. After applying global gain to the image signal, the camera performs DCS. Gain is applied prior to the DCS to avoid adding noise that would then be amplified. Offset is applied to the signal after DCS. Camera offset is selected by setting a 5-bit control word, which is sent to a digital-to-analog converter (DAC). One least significant bit equals an offset of about 8 gray levels. The maximum offset equals 248 gray levels. After offset the signal is converted to a digital value by the flash analog-to-digital converter.

Six-Position Filter Wheel System

This system is modular and functionally separate from the imaging camera. This module with minor configuration modifications is used on the Clementine UV/Vis and NIR cameras, Refs [2,3]. Six spectral bands are selectable from the filter wheel which is controlled through the SASI bus. Six filter positions are available using a space-rated 90° No. 5 stepper motor geared at 6:1. A series of Hall Effect sensors and magnets are used for position determination. A small electronics card for command and operation makes up the balance of the filter positioning system. Filter wheel control is limited to moving forward or backward one filter position at a time and reporting back the present filter position. Both the control logic and interface are implemented in a single Actel FPGA. The filter position control board is a rigid flex printed circuit board with dual thermal planes. A more detailed discussion of this filter wheel system is presented in Ref [2].

Range Receiver Module

The range receiver module contains the avalanche photodiode (APD) and detector bias and amplifier electronics. This module is illuminated by a dichroic beamsplitter and APD relay optics oriented at 90 degrees to the imaging path. The relay optics re-images the primary entrance aperture onto the APD and contain a 1-milliradian field stop. The APD electronics includethermal compensation for the APD bias voltage and programmable thresholding of the output signal. The APD current is amplified and converted to a voltage by a transimpedance amplifier with a low frequency cutoff of 3 MHz, and a high frequency cutoff of 23 MHz. This signal is further amplified, then discriminated for changes (increase) through a 14 MHz discriminator. Voltage changes exceeding the programmed threshold are flagged as returns.

The range receiver board incorporates an EG&G C30954E APD. The APD bias (300V) is provided by a gateable temperature compensated (2V/°C) bias supply. The supply is gated off during ranging to minimize noise. The APD is operated at an approximate gain of 100X. The amplification chain consists of a transimpedance amplifier, video amplifier, and voltage controlled gain amplifier. The overall amplifier gain is approximately 200X resulting in an overall responsivity of 60×10^6 V/W at 1.06µm. The time varying gain circuitry ramps the amplifier gain from 50X to 200X during the return. The discriminator is an LM360 with hysteresis. The discriminator level is set via an analog input normally provided by a D/A converter. This circuitry is implemented on a flexible printed circuit board with dual thermal planes. When folded up in the Clementine package, it occupies less than 50 cm^3.

System Controller Module

The system controller module controls the overall operation of the HiRes/LIDAR system. The system controller is built on a rigid flex printed circuit board that is interconnected to the range receiver, intensifier, camera and filter wheel modules. It communicates to the external processor via a SASI bus. This module contains a micro-controller processor and a commercial ASIC designed for a NATO issue laser range finder. The range counter ASIC carries out the range timing and binning and keeps track of the returns during a given range cycle. Range values are determined by the number of clock cycles counted following the sampling of the laser output which defines the start pulse. The available clock counter has 14 bits of resolution (a dynamic range of 16,384). For the Clementine mapping we choose a range resolution of 40 meters so that valid returns could be received at a maximum range of 640 km. This provided a working range between periselene of 400 km and the 640 km maximum range. The minimum range detection was set at 240 m. Returns from the discriminator are binned 4 to a clock count, turning the range receiver's 23 MHz response (equivalent to 10 meter range resolution) into a 40 meter range bin. Earlier work has demonstrated that better than 5 m resolution is feasible with the existing amplifier electronics design. Internal memory in the ASIC saves up to 6 "returns" per laser firing: a) first, b) last, and c) with up to 4 saved between 2 programmable range values. Threshold is set at a level that is a compromise between missed detections and false alarms.

HiRes/LIDAR Assembly Process

Modules are built and tested individually prior to integration to one another. Fig. 5 identifies the modules in this camera. The first module built is the camera module. Assembly begins with careful measurement of the CCD and camera housing to determine final dimensional stack-up at assembly. The image intensifier module is then placed into its housing and adjusted for axial location and perpendicularity based upon the CCD and camera housing measurements.

A copper heat conduction strap is fixtured and bonded to the front surface of the CCD package with Epon 828/Versamid 140 epoxy. The CCD faceplate and intensifier exit window are cleaned and primed with Dow Corning Q3-6060 primer prior to bonding with Dow Corning (DC) 93-500 aerospace encapsulating compound. The CCD is fixtured and lowered into contact with the intensifier window upon which one small drop of the 93-500 material has been applied. The fixtured assembly is loaded with a weight to apply 20 psi compressive load to the bonded joint. The assembly is placed into a small vacuum chamber and degassed at $\sim 10^{-3}$ torr for 15 to 20 minutes to remove bubbles which may be trapped in the bond. The bond is inspected prior to adhesive cure by attaching the camera PWA to the CCD via a cable and functionally inspecting the joint by operating the image intensifier against a dimly illuminated background. The bond joint is allowed to cure for 7 days at 25°C. After cure, the space between the front surface of the CCD package and the rear surface of the intensifier package is potted with DC 93-500 material to provide mechanical stability to the optical window bond joint.

The intensifier housing with CCD is mated to the camera housing. Thermal conduction between the CCD and camera housing is achieved using Dow Corning Q5-8003 thermal compound and small linear wave springs which provide mechanical loading between the CCD and intensifier at completed assembly. The camera PWA is installed into the camera housing from the rearward direction, fastened in place, and the rear camera cover attached. The assembly is held together temporarily by fixturing.

The filter wheel assembly is composed of a wheel containing 6 bandpass filters, a No. 5 stepper motor which rotates the wheel via a spur gear drive, and an electronic controller PWA which drives the motor and determines filter position. Filters are bonded into the filter wheel using Armstrong A-12 epoxy. Magnets are installed into the filter wheel which actuate Hall Effect sensors on the control PWA for position determination. The PWA and filter wheel are assembled into the filter wheel housing and the bearings are preloaded to provide rotational damping during operation. The stepper motor is installed and the

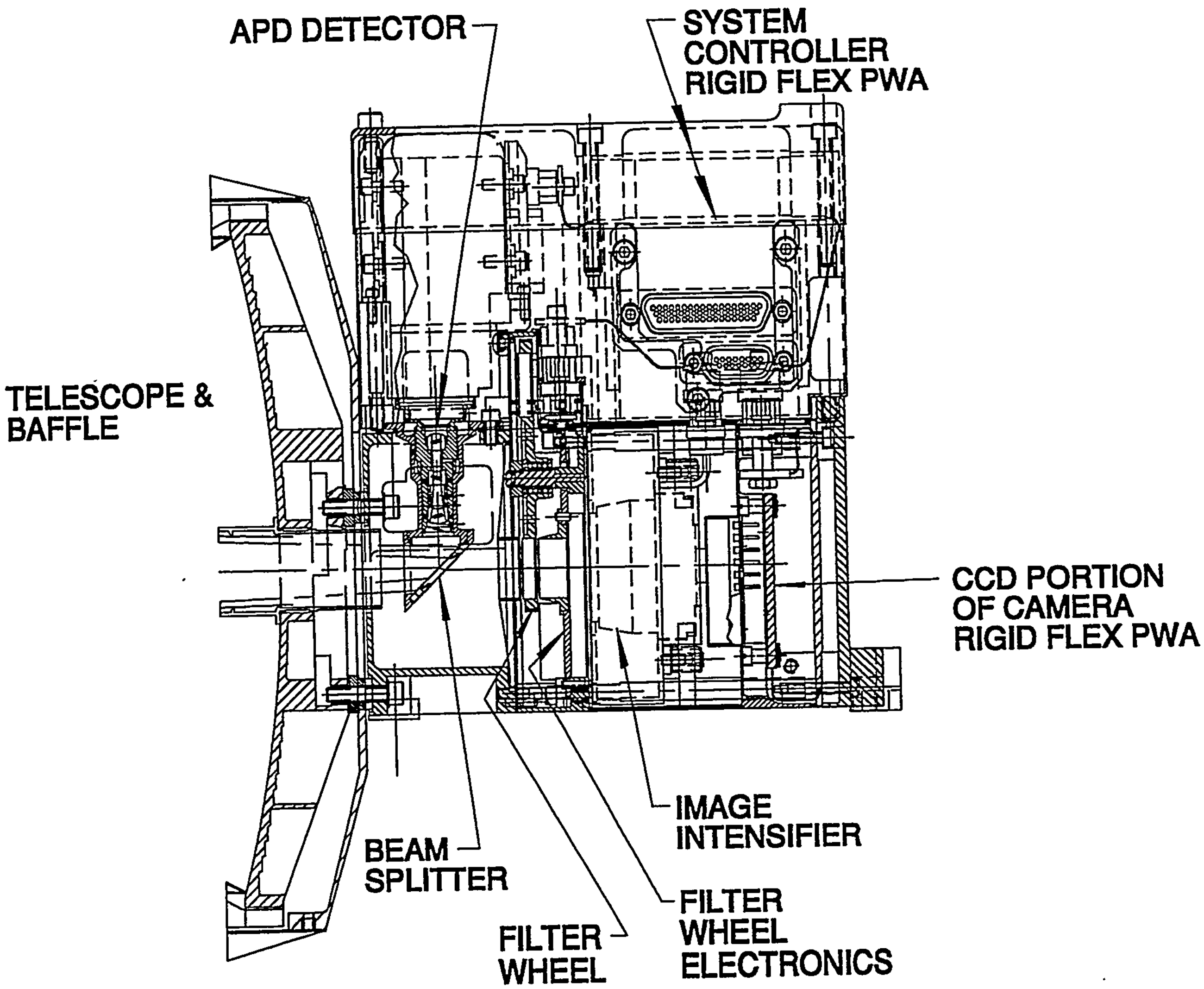


Figure 5. Select details of the Clementine HiRes/LIDAR camera.

filter wheel assembly actuated. The motor is rotated in its mount to time the filter wheel for best operation. The filter wheel assembly is mated to the beryllium interface housing which attaches the all-beryllium telescope to the sensor.

The dimension from the front mating surface of the intensifier housing to the center of the intensifier input faceplate is measured and used in determining telescope focus. The beryllium telescope, interface housing, and filter wheel subassembly is mounted onto fixturing at the exit of a collimated light source and the position of best focus is measured on-axis and at several points off-axis with a measuring microscope to determine the best fit location of the curved telescope focal surface. Telescope axial location in the final assembly is determined by subtracting the dimension to the intensifier faceplate from the measured focal surface location of the telescope at the rear of the filter wheel housing. The three focus spacers (spherical washer sets) are machined to the calculated length which brings the telescope into focus at the intensifier faceplate.

The camera/intensifier subassembly is mated to the telescope/interface housing/filter wheel subassembly and attached using special fasteners which tie all of the modules together into the imaging unit. The imaging unit is placed onto a prealigned fixture at the exit of the collimated light source for boresighting. Boresighting alignment is accomplished by carefully lapping selected focus spacers until the telescope is tilted into correct alignment (23 microinches removed from a spacer moves the boresight 1 pixel). Boresight tolerance is ± 5 pixels (±100 microradians) from CCD center.

With the imaging unit correctly boresighted, the ranging optics are aligned visually using optical alignment targets. The range receiver optics are fixed into place by "liquid pinning" whereby a small metal sleeve is placed over a fixed dowel pin and the annular gap between the sleeve and surrounding part is filled with epoxy material. This process provides positional control without the need to match drill and pin the assembly, and it also avoids contamination from metal particles.

The system controller housing is attached to the imaging unit. The range receiver module, consisting of an avalanche photodiode, preamplifier, and high voltage power supply, is installed into its correct location within the housing. The system controller PWA (which controls the functioning of the image intensifier, range receiver, and range counter) is installed into the housing with thermal compound at all contact points to aid in conduction of heat out of the circuit assembly. The system controller cover is installed onto the controller housing effectively protecting the PWA inside and acting as a further heat conduction path out of the circuit assembly.

The telescope baffle is installed onto the baffle support which was previously installed onto the interface housing and isolated with ULTEM 1000 polyetherimide washers to act as thermal breaks. The baffle, consisting of multiple sharp-edged circular apertures welded into a cylindrical stepped/tapered housing, is blackened using a black copper oxide electrochemical process, as previously mentioned. The resulting surface has extremely low gloss and reduces stray light problems which would occur when the instrument views dim objects adjacent to bright sources.

LASER TRANSMITTER ASSEMBLY

The high output power laser is a Q-switched diode-pumped Nd:YAG unit developed by McDonnell Douglas Electronic Systems Company. The laser transmitter assembly consists of two components: a laser head and a power supply module. Fig. 6 shows a photogragh of the flight laser transmitter assembly, and Fig. 7 shows a schematic drawing of the assembly. Table 2 lists the performance specifications and Fig. 8 contains a functional block diagram of the laser transmitter assembly including both the laser head and power convertor modules. The laser output is nominally 180 mJ/pulse with 171 mJ at 1064 nm and 9 mJ at 532 nm, with <10 nsec pulse widths. The doubled output allows active imaging experiments close in to the LIDAR system and some optical alignment flexibility. The beam divergence meets the design requirement of <500 microradians at 1064 nm. The beam profile is a very close fit to a Gaussian (>80%). The laser can be operated continuously at a 1 Hz rep rate and could be run in a burst mode at higher rep rates. The laser required 6.8 W at 1 Hz repetition rate to range the lunar surface from an altitude up to 640 km. An 8 Hz repetition rate with a 400 pulse limit was planned for the Geographos flyby.

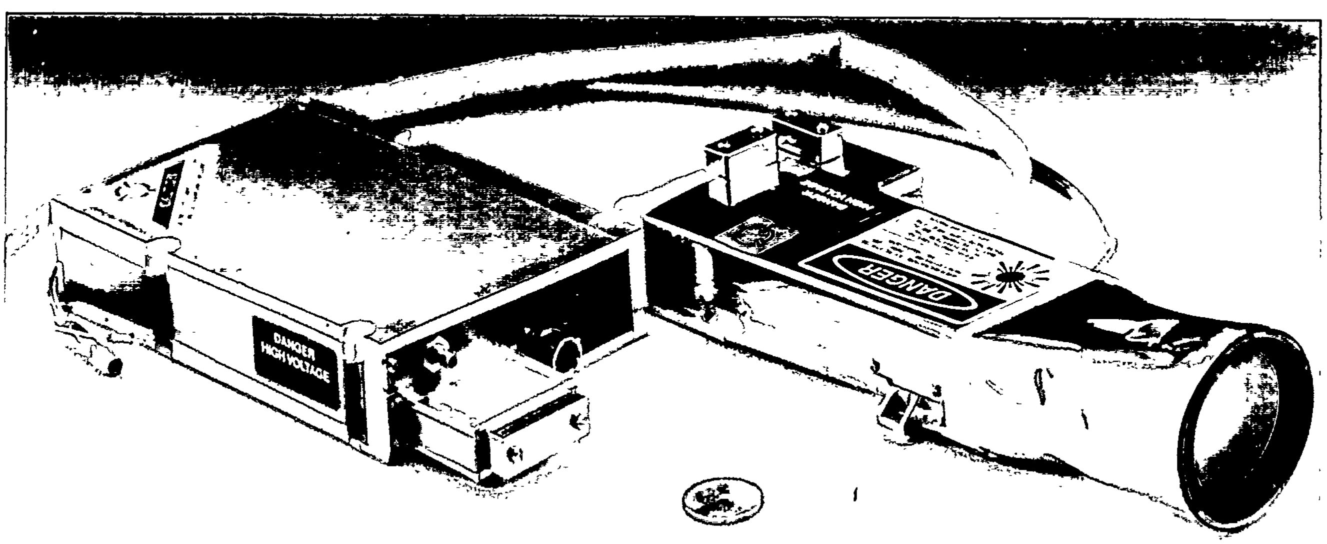


Figure 6. Photograph of the Clementine laser transmitter assembly.

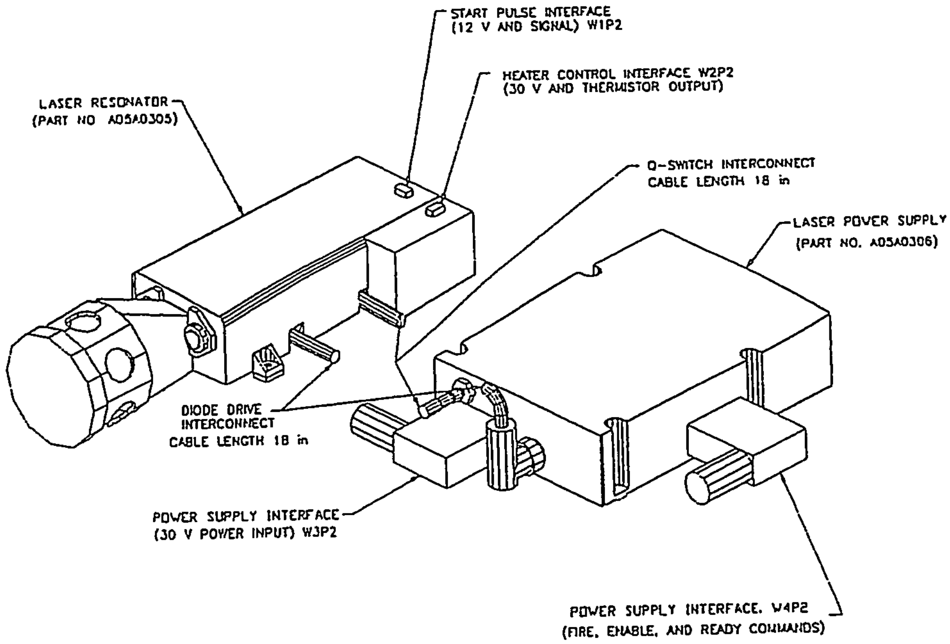


Figure 7. shows a schematic drawing of the Clementine laser transmitter assembly.

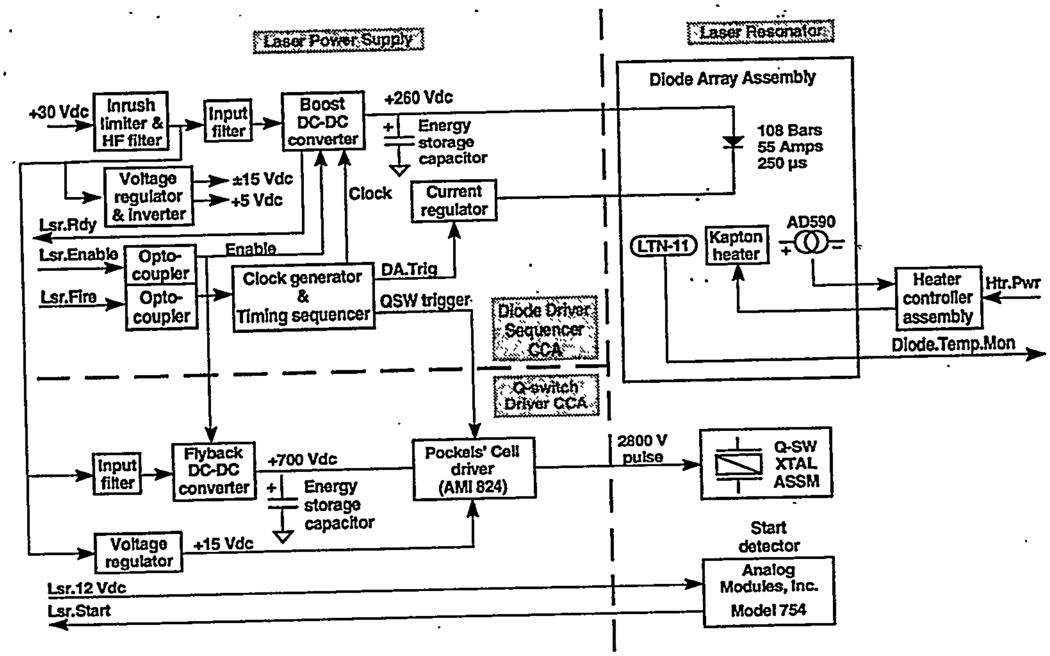


Figure 8. Clementine laser transmitter functional block diagram.

Table 2. Laser transmitter assembly performance specifications.

Attribute	Characteristic
Laser	
Wavelengths	532 nm/1064 nm
Pulse energy	171 mJ @ 1064 nm 9 mJ @ 532 nm
Pulse width	< 10 ns
Beam divergence	< 500 µrad @ 1064 nm 4 mrad @ 532 nm
Beam profile	> 80% Gaussian fit
Shot profile	Continuous (1 Hz); 400 shots (8 Hz)
Optics	
Type	5X Galilean-type telescope
Clear aperture	38 mm
Speed	F/2.6
Electronics	
Start pulse detector	Analog Modules, Inc. Model 754
Pockels' cell driver	Analog Modules, Inc. Model 824
Laser diode heater	Minco Kapton film resistance type
bandwidth	16° to 18°C
control feedback	AD590 thermistor
heater resistance	89 ohms
Power	6.8 W at 1 Hz, 36 W at 8 Hz, 2.6 W quiescent
Physical/Thermal	
Mass laser head	635 grams
power supply	615 grams
Size laser head	5.7 cm x 7.8 cm x 23.7 cm long
power supply	13.3 cm x 15.2 cm x 3.9 cm high
Temperature Range	Operating / Non-Operating
Laser head	15° to 35°C / -35° to 70°C
Power Supply	-20° to 50°C / -35° to 70°C

Laser Head

The laser head uses a polarization-coupled U-cavity resonator design that had been previously qualified for tactical military applications. Fig. 9 shows a photograph of the hardware implementation and Fig. 10. shows the laser resonator optical layout. The standing wave resonant cavity is bounded by two Porro prisms and is folded by a corner cube. The Porro prisms have Risley wedges to allow for beam alignment. The Porro prism assembly in the Q-switch leg has a 0.57λ waveplate to allow polarization compensation. This cavity design exhibits excellent beam pointing stability because of its crossed Porro prism resonator design utilizing a zig-zag slab gain medium. The gain medium is a diode pumped nine-bounce trapezoidal slab of Nd:YAG. The Nd:YAG slab is configured for single side pumping with single-side heat removal. An AR coating is used to couple the pump energy into the long side of the slab, where the laser diodes are located. A high reflectance coating on the shorter side to reflects the pump energy back into the gain medium. The short side interfaces to the heatsink. The zig-zag path through the slab provides an efficent means of cancelling optical distortions due to non-uniform gain, thermal effects, or crystal imperfections. Output coupling is achieved with a λ/2 waveplate, λ/4 waveplate and a polarizer cube. The cube polarizer directs the outcoupled pulse to an optical turning prism and then finally to the beam conditioning optics. Laser oscillation dynamics (i.e. build-up and cavity losses) are controlled by a lithium niobate ($LiNbO_3$) Pockels cell assembly (Q-switch). The Q-switch acts to vary the cavity loss by changing the polarization state of the return light incident on the polarizing cube. The Q-switch is placed in the low circulating power potion of the cavity to ensure that its laser damage threshold will not be exceeded. The beam divergence of the laser resonator is 2.0 mrad (at the $1/e^2$ point). A 4x beam expanding and collimating telescope reduces the divergence to nominally 500 µrad. The telescope is a simple two element f/3 refractive Galilean telescope.

Thermal control elements maintains the temperature of the pump diodes and the gain slab to within a 12° C control band (10° to 22°C). The laser head contains an integrated hybrid laser optical receiver, an Analog Modules, Inc. Model 754 device which contains a photodiode, amplifier, pulse strecher, and output buffer assembled within a hermetically-sealed package. This device generates the start pulse (fire detection signal) for the HiRes/LIDAR's system controller module.

Power Converter Module

The power converter module consists of a diode laser driver/power converter circuitry, Q-switch driver and energy storage capacitor. The diode laser driver/converter provides the electrical input to the pump diodes. The nominal input voltage is +30 Vdc from the spacecraft bus. When an active laser enable signal is sent via the interface, the boost covertor chargers the energy storage capacitor to a predetermined voltage. A laser ready signal is output via an opto-isolated interface after the capacitor has been charged. When the laser fire signal is activated, the timing sequencer generates a trigger signal to the diode array current regulator and a constant current pulse drives the diode array. The timing sequencer also generates a synchronized trigger to the Q-switch driver. After the laser fires the fire detection signal is generated in the laser head to restart the cycle.

ENGINEERING HOUSEKEEPING DATA CHANNELS

Several parameters were monitored to track the health of the cameras over the mission duration. These were image quality (dark level), CCD temperature, camera current levels, camera voltage levels and lens heater current. Additionally, switches were monitored to indicate ON/OFF status. For the laser head, the temperature of the Nd:YAG slab was monitored.

Temperatures were measured with Fenwall LTN-11 thermistors (purchased with calibration curves), with each thermistor bonded in place with Tra-Bond 2151 thermally conductive adhesive. The CCD thermistor was mounted flush with the backside of the alumina carrier package of the CCD, and was captured by a machined slot in the camera housing.

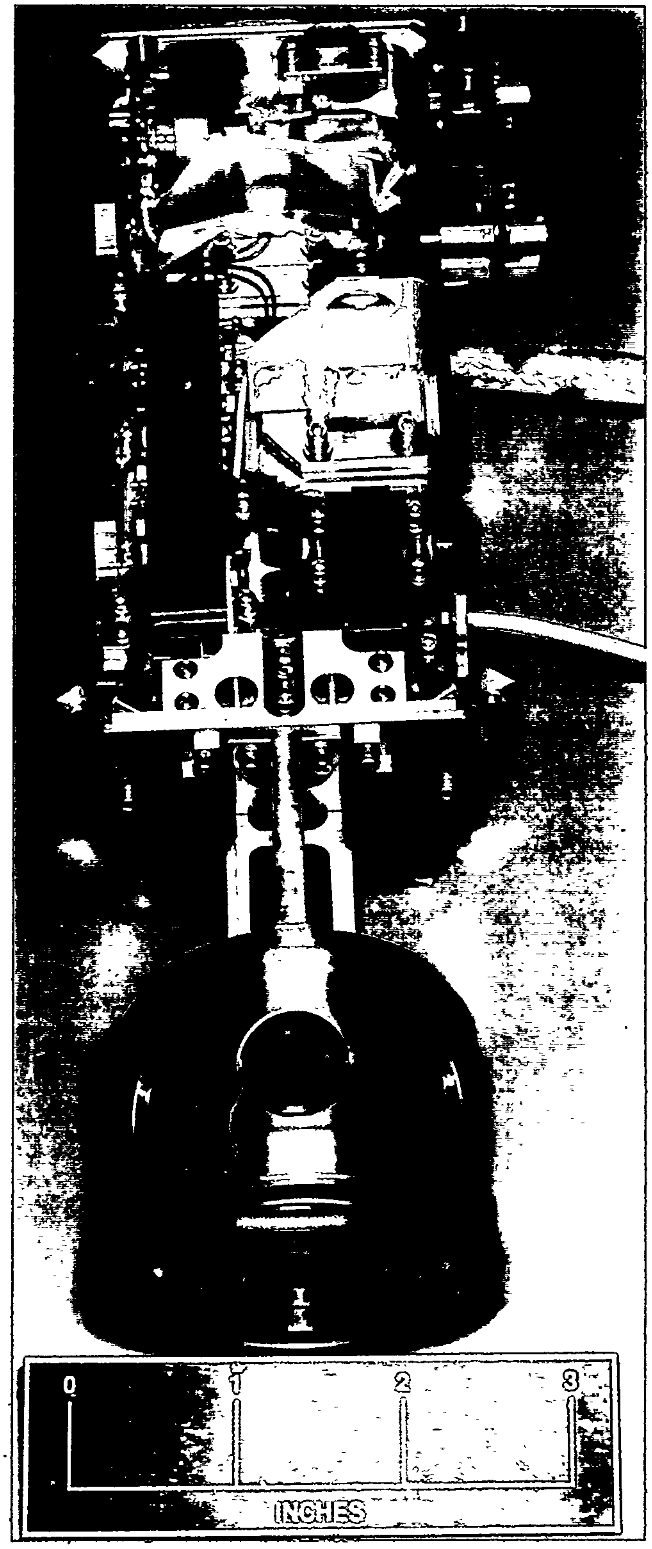


Figure 9. The laser head of the Clementine laser transmitter assembly with covering removed shows it's construction.

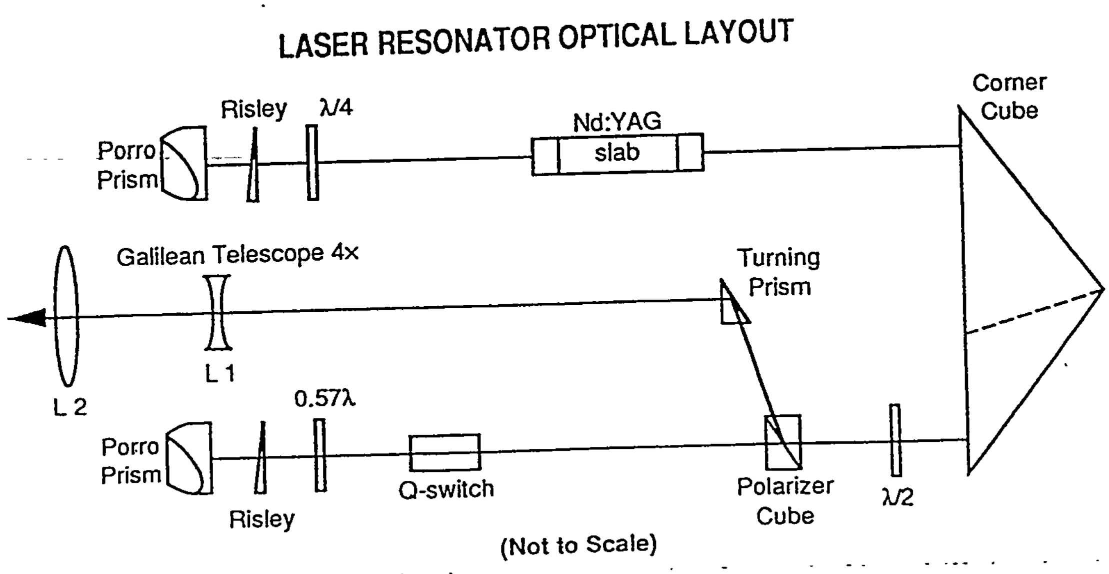


Figure 10. Conceptual layout of the laser head optical design.

INTERFACES

Camera interfaces (optical, mechanical, thermal, electrical and communication) were defined with the spacecraft integrator (Naval Research Laboratory) prior to, and modified during, camera development. An interface control document (ICD), Ref [7], provided working constraints between LLNL and NRL.

The camera is bolted to the spacecraft at the camera mounting plate with three No 4-40 fasteners. Several Al 1100-0 thermal straps were attached at the camera (CCD and various points of the electronics chassis) and directly to the camera heat pipe (part of the spacecraft Thermal Control System). The camera was thermally isolated by a MLI blanket, and the protective panel used in front of all the cameras. The camera communicated to the spacecraft processor via a synchronous addressable serial interface (SASI) bus protocol based on the Goddard Flight Center (GSFC) 650C custom PMOS process digital integrated circuit. Digital lines were CMOS tri-stated differential line drivers and receivers based on RS-422.

FLIGHT QUALIFICATION DESIGN, ANALYSIS &TESTING

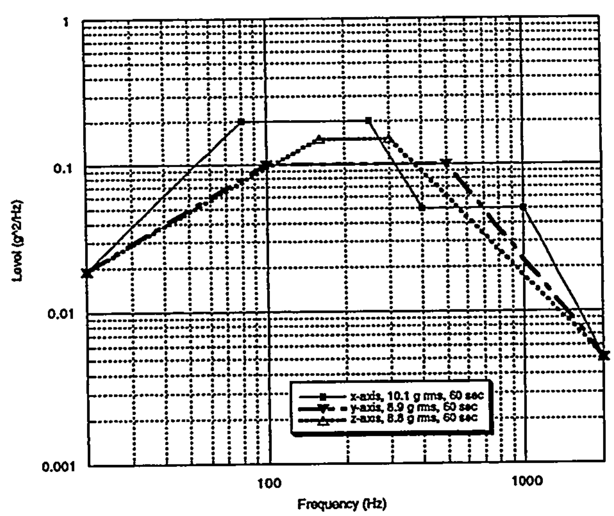
Cameras and the laser transmitter assembly were designed, analyzed, developed and subjected to critical peer review (design reviews and test data reviews). Each unit was subjected to extensive testing to measure compliance with interface definitions and show basic functionality, determine compliance with environmental test requiremnents, and to characterize the electro-optical preformance in response to expected viewing scenes. Prototype units were built to act as a pathfinder during each phase of development testing. These prototypes were also aggressively used in integration activities to find problems early thereby maintaining schedule.

Environmental testing was performed in compliance with the Clementine program guidelines and MIL-STD 1540B "Test Requirements for Space Vehicles". Tests included radiation resistance (for the electronic components), random vibration, thermal cycling, thermal vacuum and electronic burn-in. Table 3. summarizes the test environments.

CHARACTERIZATION AND CALIBRATION

Extensive pre-flight calibration data were acquired using an automated calibration facility at LLNL. In a typical calibration configuration, a sensor was mounted inside a dry nitrogen environmental chamber whose temperature was varied systematically over the range -20 to 20 °C, the expected operating temperatures for the mission. Depending on the measurement types the sensors saw either a flat diffused light source or a collimator with various pinholes as the point source. A custom board controlled the sensor parameters from the host computers; the video signal was acquired using a commercial image processor. During data acquisition many thermal parameters such as CCD and chamber temperatures were monitored and recorded as part of the image structure. All calibration processes were highly automated, enabling us to acquire data quickly and reduce operator errors. Pre-flight calibration attempted to cover similar light levels expected from space and the lunar surface and spanned the same camera settings required for lunar mapping phase.

Table 3. Clementine HiRes/LIDAR camera environmental analysis and testing.

<table>
<tr><td>Space Radiation</td><td>20 krad (at Silicon) total dose, by component selection or by shielding</td></tr>
<tr><td>Derived Structural Loading Requirements</td><td>• Factors of safety 1.10 (yield), 1.25 (ultimate)
• 100 g's steady-state loading in each axis
• 14 g rms random vibration from 20-2000 Hz
• 84 g peak acceleration for pyro-shock
• >50 Hz output frequency</td></tr>
<tr><td>Random Vibration</td><td>


</td></tr>
<tr><td>Thermal Cycling</td><td>-30°C to 20°C, six cycles</td></tr>
<tr><td>Thermal Vacuum</td><td>-25°C to 5°C, 1 cycle</td></tr>
<tr><td>Electronic Burn-in</td><td>>300 hours</td></tr>
</table>

The pre-flight calibration measurements included radiometric sensitivity; CCD uniformity; gain and offset scale factors; temporal/spatial noise; dark noise dependence on CCD temperatures, integration times or input voltage levels, spectral response of CCD; optical distortion map; point spread function and electronic warm-up time. Ref [8] provides a more complete description of these calibrations.

Many pre-flight calibration coefficients were applied to lunar data showing reasonable agreement with expected performance. In-flight calibration data will allow minor corrections for vacuum flight condition and sensor degradation over mission lifetime to be added to the pre-flight calibration results.

CLEMENTINE MISSION DATA

The HiRes/LIDAR was operational throughout the entire duration of the Clementine mission, showing no degradation in its performance. There was concern early in the lunar mapping phase of the mission that the brightness of lunar surface would cause a degradation to the intensifier performance through charge migration effects from the photocathode. This mechanisim

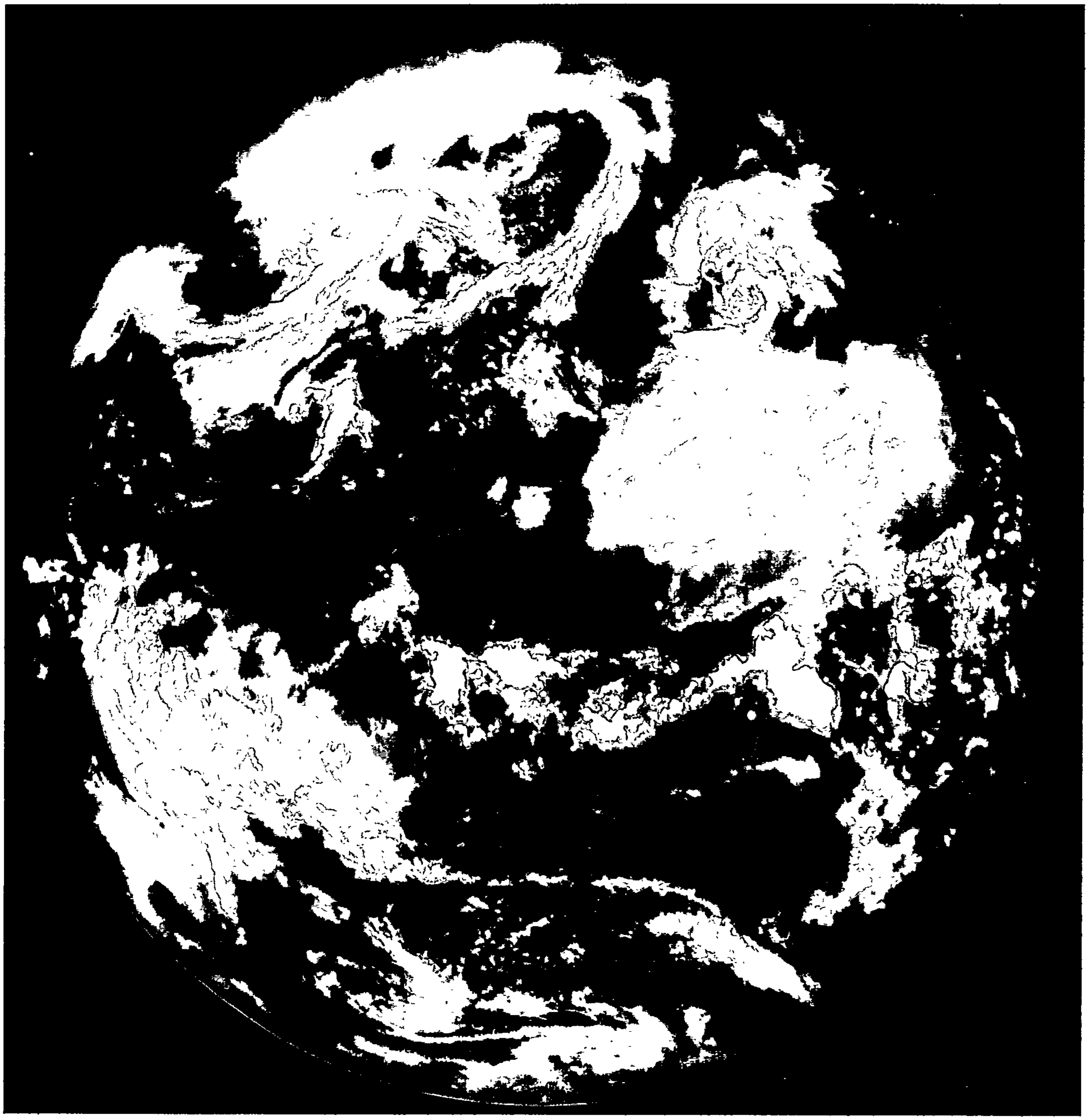


Figure 11. Over 70 HiRes images (at 750 nm) mosaiced together show Earth as viewed from the Clementine satellite on April 11, 1994. Spacecraft attitude was adjusted to step-scan the HiRes field of view across the Earth. This composite image was taken from a distance of 384,000 km showing a 6 km resolution over a 2° x 2° field of view. North is up; Africa, Spain and the middle East are right; with So. America, Central America and Florida to the left.

is a well known life limiter of image intensifier tubes. Consequently the image intensifier was operated with relatively low gain in order to reduce loss of sensitivity during the lunar mapping mission and to insure that there was sufficient performance margin during the planned Geographos flyby. Within these operational constraints, the imaging channel provided excellent imagery demonstrating the capablity of this camera. Fig. 11 gives a mosaiced example of the Clementine HiRes camera imagery.

Lunar mapping use of the HiRes was limited to full-color bursts of selected areas and narrow strip mapping (see Fig. 12) at the extreme latitudes, where shadowing yields interesting morphology insights. To create a continuous swath with the small FOV of the HiRes camera, images were collected at as short as 0.4 sec intervals. Data compression of the HiRes camera was generally 15:1 or even greater. This is due to a number of factors, including scene content, exposure settings, and scene quality. Near the poles, the shadowed sections could occupy more than half of the focal plane, and usually did so with large, contiguous pixel regions. With data compression performed on an 8 x 8 block, entire blocks could be sumarized by a single DC level. The lower exposure levels, set to extend the lifetime of the imaging camera, provided adequate imagery for morphology studies, while typically spanning only 6 out of 8 bits of information. This, too, helped reduce the volume of compressed data. Lastly, the HiRes image quality, limited by the image intensifier blur, was not single-pixel quality (Blur was roughly 2.5 pixels). This meant that the high-frequency pixel-to-pixel variation could be smoothed (by compression) without as much loss of information as would have been seen in a higher resolution camera.

Space-look frames were taken at the end of every orbit, and were available to monitor the responsivity of the imager. The HiRes showed consistently low noise levels throughout the life of the mission. Dark field data were consistent with pre-launch calibration data taken in the laboratory.

Signal to noise (SNR) in the imager was limited by shot noise at the intensifier photocathode. This could have been improved by reducing the intensifier voltage (gain) and increasing the integration time (voltage on time), but was not due to the limitation of accumulated signal on the photocathode.

As previously discussed, LIDAR range data was limited to ranges less than 640 km by the number of bits available in the signal return detection clock and the design decision to bin range returns into 40-meter range increments. The ranger electronics has 6 internal memory bits to save signals exceeding the differential threshold limit set in the SASI interface for detection. In operation, four of these memory bits are dedicated to the search range pre-set by the user. The first four ranges triggering the threshold limit are saved to these bits, with subsequent returns inside the preset range overwriting the fourth bit. The additional two bits of memory write the last detection before the range window and the first detection after the range window that trip the threshold limit. Because the range counter had a maximum of 640 km, the operation of the LIDAR ranging was limited to 80° to 90° latitude, centered on orbit periselene. Data was taken within this swath for the duration of the mapping mission. A set of range data from a portion of one orbit is shown in Fig. 12.

The LIDAR SNR, and therefore false alarms, were influenced severely by the background scene level. The large background signal, most pronounced near the equator, served to deplete the voltage level on the APD, reducing the responsivity to a return throughout the 4.2 msec

Figure 11 This Clementine data shows a strip of HiRes images superimposed on a strip of UV/Visible images to illustrate the relative difference in ground resolution achieved and ground footprint size. The UV/Visible width is ~12.4 km, and the HiRes width is ~2.9 km. Data analysis and presentation courtesy Ref [11].

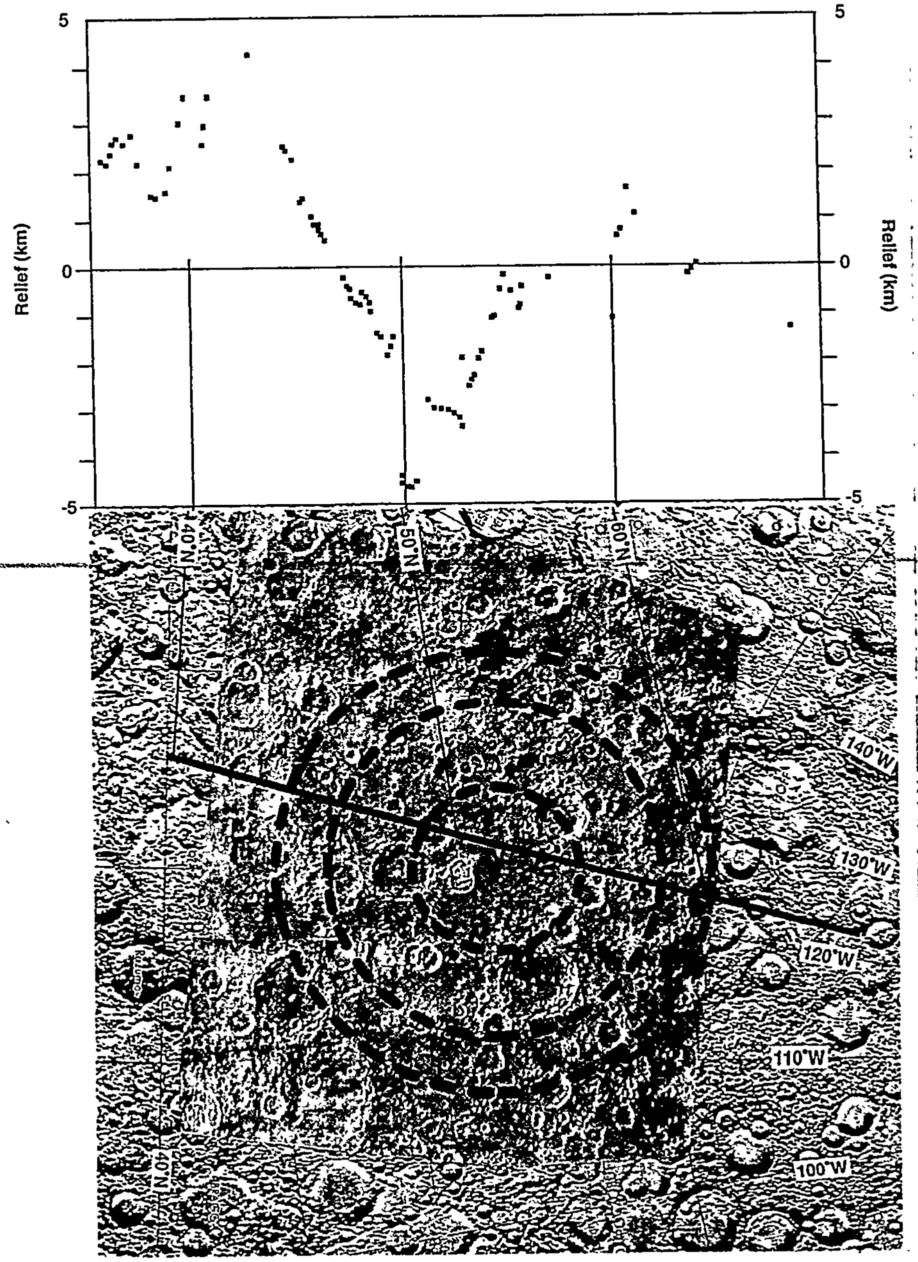


Figure 13. The top graph depicts processed range data generated by the Clementine LIDAR ranging system. This strip of range data is shown as a line through the images below the graph. The images are a mosaic from the Clementine UV/Visible camera overlain on a U.S. Geographical Survey shaded relief map of the Moon. The region is the Coulomb-Sarton Basin on the northwestern far side of the Moon. Data analysis and presentation are from Ref[10].

round trip return time that the APD is gated on. The shot noise of the background was capable of obscuring the target return with multiple false alarms if the threshold for differential signal return was set too low.

LESSONS LEARNED

Due to the time and budget constraints of the mission, some of the historically evolved design features that were set around a predecessor mission were not re-designed for optimal performance in the Clementine imaging sensor environment. Specific mission goal changes from previous requirements include the operation with bright scene backgrounds and the requirement for calibrated radiometric response.

Scene brightness increases to the HiRes system lead to lifetime concerns and usage limitations. Radiometric accuracy lead to a requirement for more control of the intensifier voltage supply. During the Clementine lunar mapping operations, capacitor charging/discharging lifetime was found to influence the requested voltage setting for an image by the previous voltage setting. This had little effect on the monochromatic morphology mapping strips, which used a single fixed filter and had voltage adjustments only at 10° latitude boundaries, but did influence spectral mapping regions. In these sections, exposure voltage was changed each image, and the filter wheel selected the spectral bands in order. With bright scenes, such as seen in the lunar mapping mission, the difficulties of an image intensifier may not outweigh the benefits, which are low-light level operation. Through most of the orbit, superior SNR and resolution would have been possible with an unintensified array (the image intensifier blurs the image).

Scene brightness (Sun reflected on the Moon) on the LIDAR system severely degraded the performance of the ranger. The APD voltage dropped as the background accumulated charge was detected. Redesigning the circuit to handle a larger background and decreasing the bandpass on the spectral filter would have alleviated most of this effect.

General design features that could have been better tuned to the mission are the range counter and threshold increment for detection triggering. The range counter, a 14-bit counter, could have been replaced with a 16-bit model, if time and budget had allowed. In order to collect the bulk of the return in a single electronic range comparator bin, and to limit the accumulated background (and shot current) a 10-nsec electronics time constant/ threshold comparator circuit were incorporated. In order to increase the range to typical orbit heights, four of these 10-meter accuracy bins were "or-ed" together into a single clocked bin, degrading the net range bin to 40-meter accuracy. A secondary improvement, also missed becuase of schedule constraints, was a reduction of the detection threshold voltage range. Threshold was programmable, with 8-bits over 2.5 V. Returns from the mapping mission seldom exceeded 100 mV. A reduction in the threshold range would have allowed better matching of the returns and discriminator, improving performance.

A final lesson would be to give stronger consideration to an optical design with an intermediate image and field stop for veiling glare reduction. The HiRes, as the other imaging sensors in the Clementine payload, does show extensive out of field veiling glare, which will be a data reduction challenge.

CONCLUSIONS

The HiRes imager/LIDAR rangefinder sensor performed consistently throughout the life of the Clementine mission. The imager provided detailed spectral studies of selected lunar sites, and provided swath maps during each orbit that will yield a plethora of morphology data. The LIDAR imager provided the first comprehensive global terrain data base at the moon, operating throughout the life of the mission. DoD sensor lifetime study goals were met by gathering a comprehensive data set on-orbit throughout the mission lifetime.

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13. We thank B. Priest for his contributions in directing and producing this article.