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The Clementine Longwave Infrared Camera

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DISCLAIMER

The *Clementine* longwave infrared camera

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ABSTRACT

The Clementine mission provided the first ever complete, systematic surface mapping of the moon from the ultra-violet to the near-infrared regions. More than 1.7 million images of the moon, earth and space were returned from this mission. The long-wave-infrared (LWIR) camera supplemented the UV/Visible and near-infrared mapping cameras providing limited strip coverage of the moon, giving insight to the thermal properties of the soils. This camera provided ~100 m spatial resolution at 400 km periselene, and a 7 km across-track swath. This 2.1 kg camera using a 128 x 128 Mercury-Cadmium-Telluride (MCT) FPA viewed thermal emission of the lunar surface and lunar horizon in the 8.0 to 9.5 μm wavelength region;.

A description of this light-weight, low power LWIR camera along with a summary of lessons learned is presented. Design goals and preliminary on-orbit performance estimates are addressed in terms of meeting the mission's primary objective for flight qualifying the sensors for future Department of Defense flights.

Keywords: Clementine LWIR Camera, Lunar Imagery, Imaging Sensors, MerCadTelluride, Ricor Cryocooler.

INTRODUCTION

The Clementine camera is a modification of earlier LWIR camera concept developed under the Strategic Defense Initiative (SDI) program for Brilliant Pebbles. A 128 x 128 pixel MCT FPA with variable gain and offset electronics and a low-weight, low-power cryocooler were transfered and combined with a modified optical design to tune the LWIR sensor for the lunar mapping mission. The spectral band was chosen along with the MCT array cut-off wavelength to optimize long-range camera sensitivty for the planned asteroid viewing portion of the mission. Optics were designed for consistency with a shared-aperture LWIR/LIDAR camera, which provided a 125 mm collection aperture. Implementation of a large-aperture LWIR camera for lunar surface imaging, where surface temperatures are as high as 400 K with emissivity approaching 1 required attenuation of the signal at the cold filter. In order to meet the planned 7-month duration space flight mission, the LWIR camera incorporated radiation-resistant materials and design practices.

In addition to generating a data set for lunar mapping, the LWIR ~~camera data can be used as a case~~ study for sensor lifetime performance on a space platform, and can be studied for valuable design lessons for future projects.

CLEMENTINE MISSION

The Clementine spacecraft was launched on schedule on January 25, 1994 from Vandenberg Air Force Base (CA). After 25 days in low earth orbit (LEO) and phasing loops, the spacecraft was inserted into an elliptical polar 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 starting the Earth/Moon phasing loops for gravity assist boost towards the near-Earth asteroid Geographos when the spacecraft suffered a software failure causing complete loss of attitude control system propellant and putting 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 [1, 2] provide good overviews and insight into utility of the Clementine data which has been analyzed.

PRIEST

LWIR CAMERA 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. Science missions centered on gathering limited lunar surface radiance data sets, that would be calibrated into temperature, for fusion with the UV/Visible and NIR data bases and studies of the temperature of the asteroid geographos (which was not completed). The LWIR, with uncooled optics, was not suitable for dark-side temperature studies, which required distinguishment between 120 K and 150 K low temeprature signals. Studies of radiation environment effects, camera noise under spacecraft platform control, and all lifetime issues were performed.

DESCRIPTION

Table 1 summarizes camera specifications. The LWIR camera, shown in Fig. 1, used a 1992 state-of-the-art Amber 128 x 128 MerCadTelluride (MCT) FPA for imaging between 8.0 and 9.5 μm. Wavelength range was controlled by a cold filter located at the end of the detector cold shield with an interference coating limiting the maximum wavelength transmitted to 1/2 μm less than the mean cut-off wavelength of the array. Detailed discussions of the signal conditioning, optics, crycooler, interface, usage, and environmental requirements follow. A functional block diagram is shown in Fig. 2.

Table 1. Clementine LWIR Camera Specifications.

Focal Plane Array	
Type	PV HgCdTe (Amber)
Pixel format	128 x 128
Pixel size	50 x 50 microns
Non-operable pixels	$\leq 5\%$
FPA operating temp	65 K
Optics	
Equivalent clear aperture	131 mm
Effective focal length	350 mm
Cold stop	F/2.67, 7.47 mm aperture
Cold shield efficiency	100%
Imaging	
Field of view	$1° \times 1°$
Pixel IFOV	143 x 143 μrad
Point spread	$\geq 60\%$ energy in 70μm slit
Temporal noise	$< 3000\ e^-$ rms @ $\tau \leq 2.30$ms, $< 4000\ e^-$ rms @ $\tau = 4.60$ ms
FPA well capacity	32 million electrons
Camera Electronics	
A/D resolution	8 bits
Frame rate (single frame mode)	52.5 Hz
Pixel rate	500 kHz
Integration times	0.115, 0.92, 2.30, and 4.60 ms
Digitization gain	3,400 to 125,000 electrons/count
Offset control	8 bits
Dynamic range	7000
Power	13.0 W
Cryocooler	
Type	Ricor K506B integral Stirling with H-10 FPA temperature closed-loop control electronics
Avg power	11.0 W steady-state
Mechanical	
Mass	2.1 kg
Envelope	14.7 cm dia x 39.1 cm long

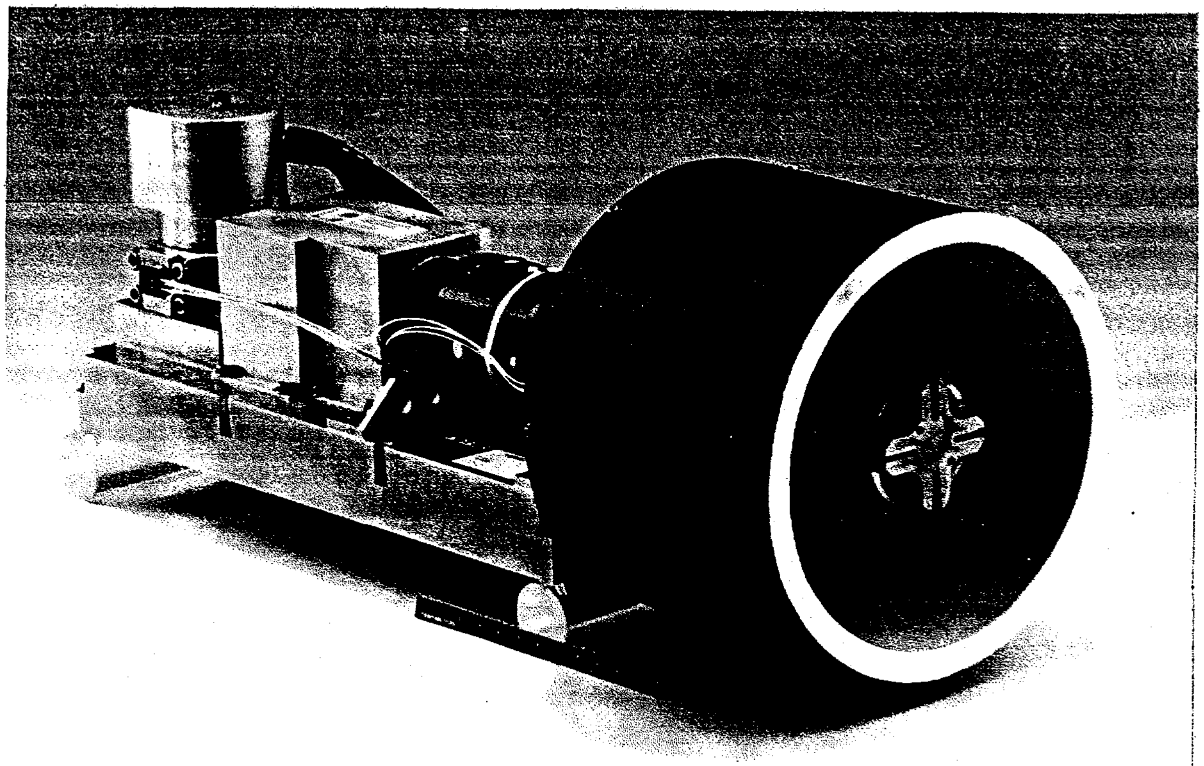


Fig. 1. Clementine long-wave infrared camera.

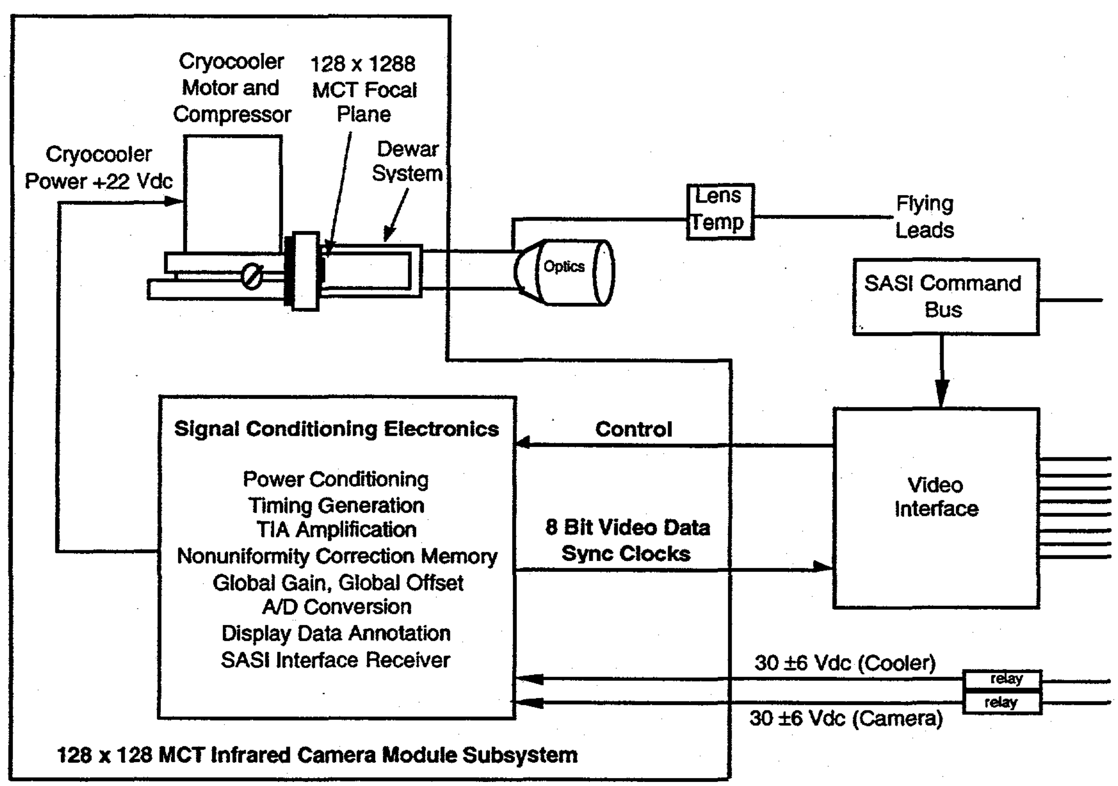


Fig. 2 Clementine LWIR Camera functional block diagram.

Optical System

The optical characteristics of the LWIR camera have been previously summarized in Table 1. The optical system is shown in Figure 3. The 1° x 1° field was taken from the predecessor sensor optical design requirements. Several performance requirements drove the theoretical design to its present configuration. These are, in roughly the order of importance, 1) shared aperture design goal of the predecessor design, 2) field of view, 3) passive athermalization, and 4) 100% efficient cold shielding. These combined requirements drove the design to a catadioptric configuration, using ZnSe and ZnS refractive optics. Refractive material selection was made for athermalization improvement. Placing the bulk of the power on mirror elements allowed better athermalization and greatly reduced chromatic requirements on the remaining optics. The F/number of 2.7 represents a 125 mm entrance pupil diameter and a 350 mm focal length. The entrance pupil was maximized, as constrained by image quality, to allow the sensor to collect the strongest signal possible due to historical design requirements. Effective emissivity of the optics, coming from the low emissivity optics/coatings and black anodized internal lens housing, was minimal, and estimated to be 20% from in-flight dark frame data.

The lunar surface radiance at 400 K was bright enough to require additional attenuation of the signal, even at the fastest design clock rate possible for the sensor. A reflective coating was added in addition to the 8.0 to 9.5 μm interference coating to reduce the signal to 30% of nominal.

Ruggedization of the assembly was achieved by potting the individual elements into an aluminum barrel, and sizing the RTV thickness to the value needed to compensate the thermal shrinkage difference between the housing and lens materials.

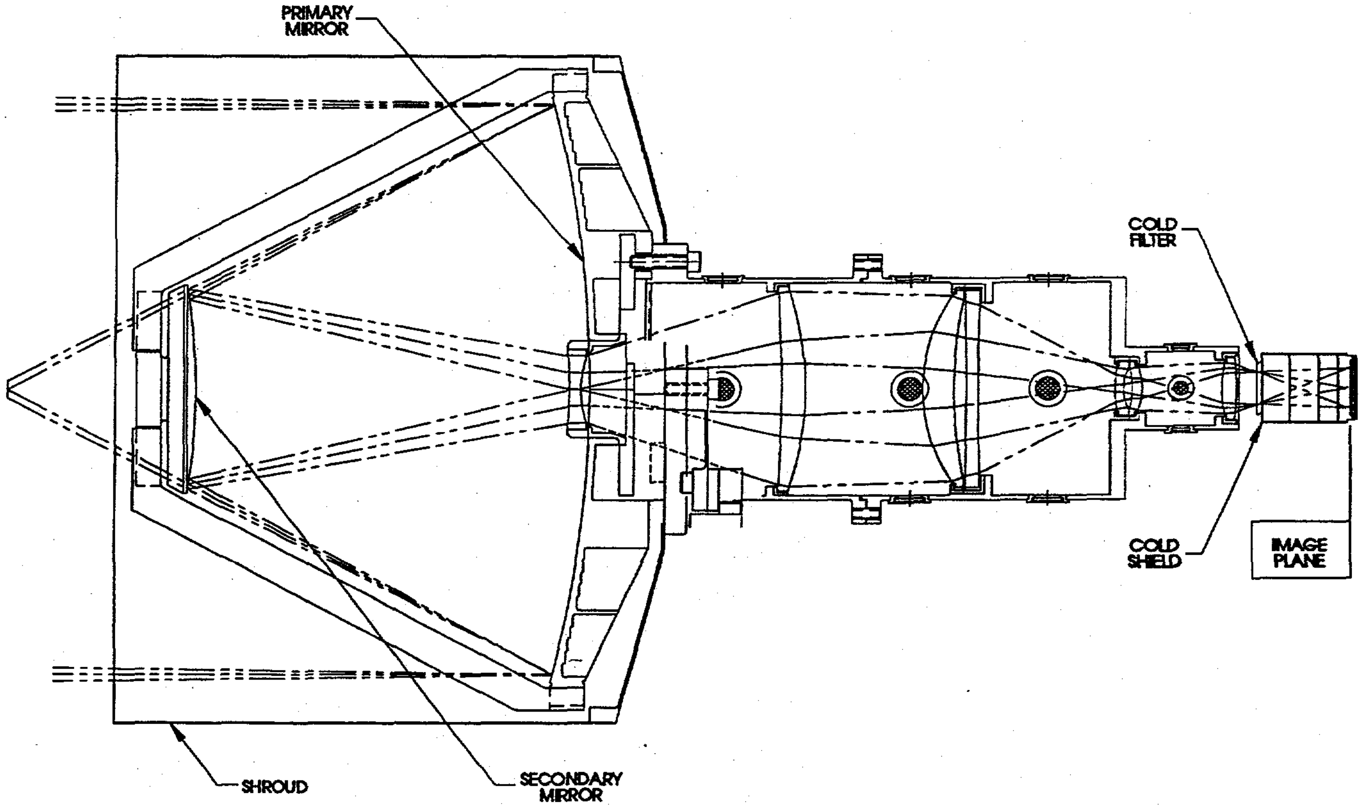


Figure 3. Clementine LWIR camera optical system.

Signal Conditioning Electronics

A single circuit board was designed for use with the 128 x 128 (2 channel) LWIR FPA and the 256 x 256 pixel (single channel) NIR FPA. Since the program schedule was of primary importance, a single design was produced to accommodate both varieties of sensor arrays. The only difference between the NIR and LWIR implementations involved the use of two specific Actel field-programmable gate arrays (FPGAs) which were mounted to the board.

The image contrast and brightness adjustments (i.e., global gain and global offset) as well as minimal pixel nonuniformity corrections were performed in the analog domain on the circuit board. Early in the program, decisions were made concerning the use of analog operations so as to reduce the overall size and power dissipation characteristics of the system. These analog operations were accomplished by using analog switches to modify resistance values which in turn changed the gain and offset characteristics of amplifier stages.

The detailed block diagram of Fig. 4 indicates the functions and how D-to-A converters were used to produce the analog operations, and how 8-bit digital data was produced from the video information as well as annotation data which was incorporated into the video data stream. Information such as camera identification code, integration time, global gain, global offset, focal plane array temperature (8-bit value in the range from roughly 58K to 83K) and detector array bias voltage (8-bit value which indicates, to first order, the total dose radiation that the focal plane has experienced) were incorporated into the (selectable) annotation data position in the 129th row of data following the image data.

Numerous camera commands were accommodated through the use of a Synchronous Addressible Serial Interface (SASI) interface protocol system utilized throughout the spacecraft system. The digital control interface electronics included in the electronics design decoded the SASI commands, and responded to respective commands with changes in camera settings. A status word was produced by the camera which echoed back the result of directed changes to the camera settings.

Another important attribute of the camera electronics was that they were designed to be immune to solar protons or other energetic particles. No memory devices were used which could be affected by radiation-induced conditions; all parts used in the design were tolerant to at least a 20 krad(Si) total dose condition.

The single circuit board included two thermal planes which proved to be effective in removing heat generated by on-board components. A variety of thermal vacuum tests were performed to qualify the electronics at operating temperatures representing those expected to be encountered during the deep space mission.

Sensor Engines

Sensor engines, consisting of the MCT FPA, vacuum dewar, dewar/electronics interconnect cable harness, and cryocooler (with FPA temperature control electronics) had a total mass of roughly 500 grams. These were the same for both IR cameras, with small differences in each unit's dewar cold stack to accomodate the different size arrays. The dewar cold stack included the FPA, cold shield, cold filter and adapters to get from the FPA to the end of the cold finger. The cold stack mass and consequently its thermal mass were minimized and the stack was held together with vacuum compatible epoxies.

The function of each flight cryocooler was to cool the focal plane array to the desired operating temperature, and maintain that temperature within ± 0.5 K, for the projected seven month life of the Clementine mission. A modest duty cycle projected the total mission operating time for each IR camera at less than 1000 hours. Additionally, 500 hours of operation was estimated for pre-launch testing, camera calibration and environmental testing. The target temperature for the MCT FPA operating in the LWIR was 65 K based on the desired radiometric performance goal for this camera.

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 [3], provided working constraints between LLNL and NRL.

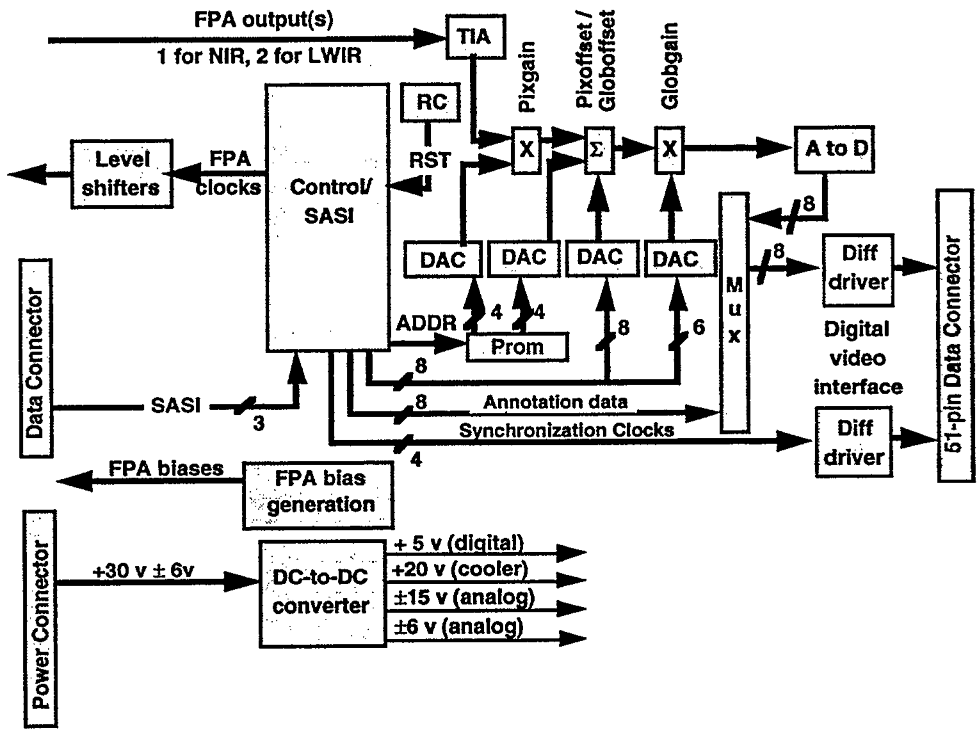


Figure 4. A detailed block diagram shows all necessary power conditioning, camera control and spacecraft interface electronics that were included on a single circuit board. Pixel gain and offset correction as well as global gain and offset control are implemented in the analog domain.

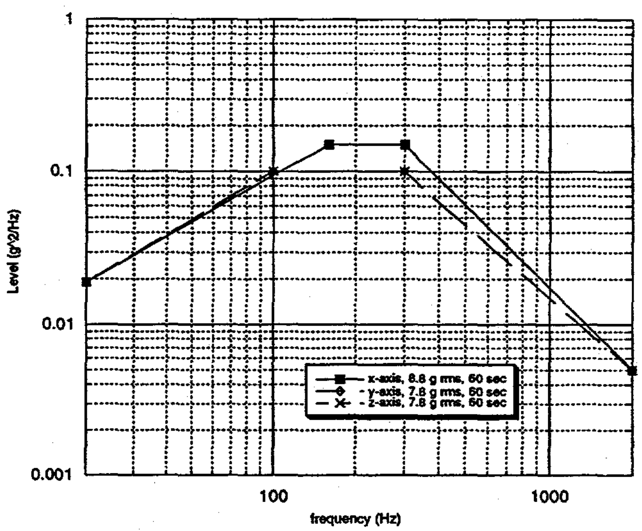
The camera required eight No. 4-40 bolts to attach it to the spacecraft. One 1100-0 aluminum thermal strap was used for interfacing to the Spacecraft thermal management system (attached to the cryocooler stator). The camera communicated to the spacecraft processor via a synchronous addressable serial 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

Camera designs were designed, analyzed, developed and subjected to critical peer review (design reviews and test data reviews). Each camera 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, random vibration, thermal cycling, thermal vacuum and electronic burn-in. Table 2 summarizes the test environments.

Table 2. Clementine LWIR Camera Environmental Analysis and Testing.

Space Radiation	20 krad (at Silicon) total dose
Derived Structural Loading Requirements	• 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
Random Vibration (Protoflight actuals)	
Thermal Cycling	-30°C to 20°C, six cycles
Thermal Vacuum	-20°C to 0°C, one cycle
Electronic Burn-in	> 300 hours

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 an environmental chamber whose temperature was set to -20 to 20 °C which was the expected operating temperatures for the mission. Depending on the measurement types the sensors saw either a flat diffused light source or an off-axis 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 FPA and chamber temperatures were monitored and recorded as part of the image structure. All calibration processes were fully automated enabling us to acquire data quickly while reducing operator errors. Pre-flight calibration attempted to cover similar light levels expected from the lunar surface and spanning the same camera settings required for lunar mapping.

The pre-flight calibration measurements included radiometric sensitivity; FPA uniformity; gain and offset scale factors; temporal / spatial noise; dark noise dependence on FPA temperatures, integration times, input voltage levels, spectral response of FPA; optical distortion map; point spread function; electronic warm-up time and cryocooler cool down time. For the thermally sensitive LWIR camera, the noise measurement was performed using a vacuum chamber to simulate the space thermal environment.

CLEMENTINE MISSION DATA

The LWIR camera was operational during the entire Clementine mission, showing no signs of performance degradation throughout the life of the mission. In the pre-lunar mapping portion of the mission (LEO/cruise to the moon), the sensitivity of the LWIR was verified by imaging whole-earth, whole-moon, and bright stars. As expected, the signal gathering capability of the camera was not capable of stellar imaging.

Lunar mapping operation covered the entire south pole to north pole latitudes in an orbit that deviated ± 30° from sun synchronous over the 60 days of mapping. Pole-to-pole coverage was completed in roughly 1.5 hours of the 5 hour orbit duration. Images for lunar mapping were taken often enough to provide roughly 10% overlap between adjacent frames when the LWIR was operating. Near the poles, where range to the moon was on the order of 1000 km, the time between images was on the order of 2 minutes; near the equator (periselene), the frequency increased to roughly 1/2 minutes between images. Data was not compressed during the Clementine mission. This decision was based on the limited total bytes taken by the LWIR during an orbit and the extreme high frequency structure seen in each image due to FPA temperature variations.

Camera integration time, offset, and gain controls were set by a spacecraft control file, which switched instructions every 10° latitude. Throughout all lunar mapping segments, optimal exposure settings used the minimum integration time, with gain adjusted slightly between equator and poles to compensate radiance. Offset was continually increased throughout each orbit to keep the data on-scale as the thermal background signal from the FPA increased. A calibrated image is shown in Fig. 5.

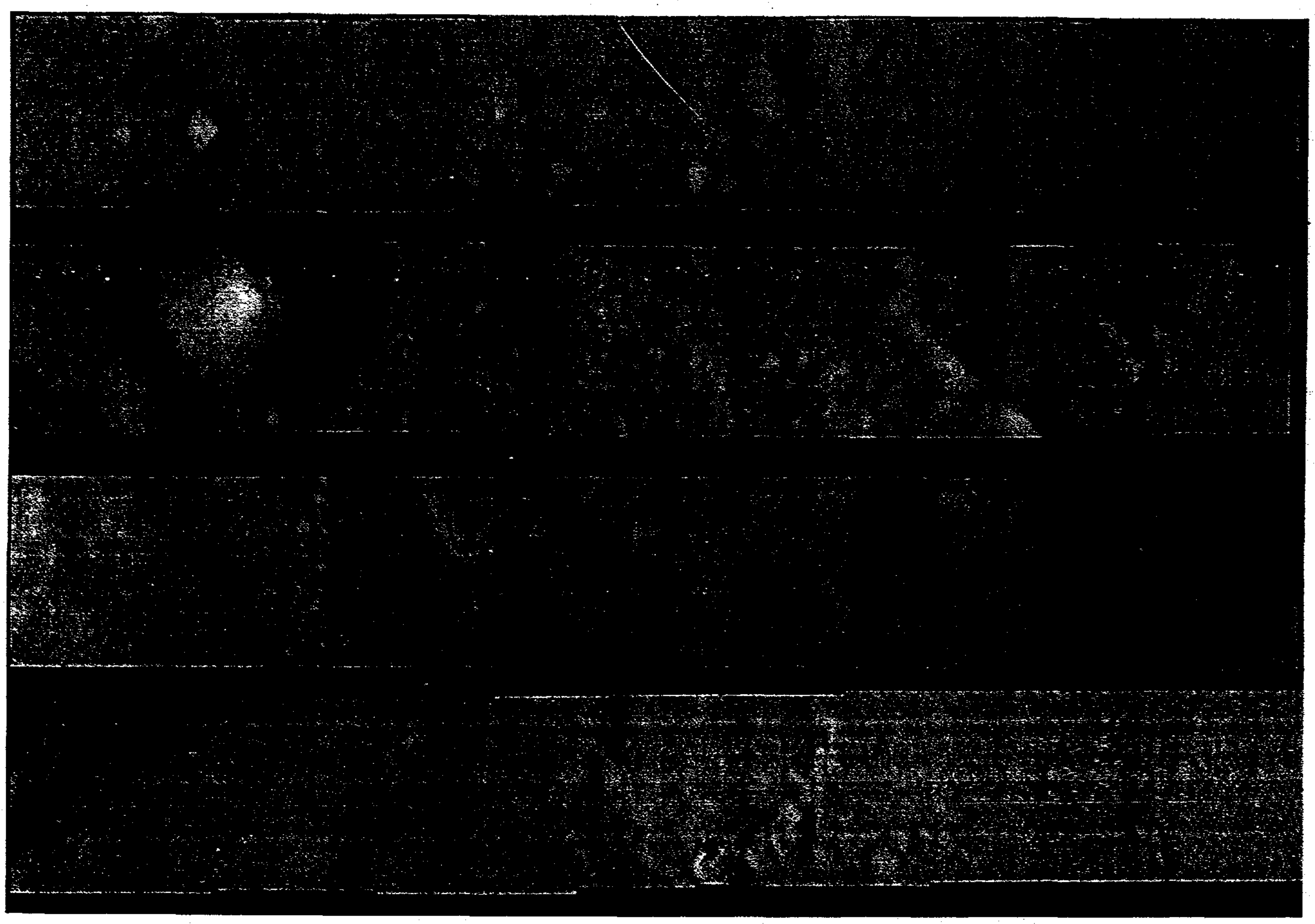


Figure 5. LWIR image strip of the moon, here viewing the Aristarchus region, with ground calibration data applied. There are four strips shown for convenience, with the upper right of one strip continuing at the left of the strip below it. North is to the right.

In addition to the 1.5 hours of lunar images, a series of uncompressed space-looking frames (away from the sun, moon, and earth) were taken at the end of each orbit and usually at the beginning of each orbit, too, for use in image calibration and sensor performance checks. The most challenging data interpretation feature of the LWIR camera is the extremely large dark-frame signal, which varies with lens and FPA temperature and therefore with time in the orbit. The magnitude of background change is several times the total signal seen at the equator. Temperature of the LWIR camera follows the heat reject temperature (_Y variable conductance heat pipe) and the spacecraft optical thermal bench temperature. The FPA temperature is minimum about 15 minutes after the beginning of the cool down sequence. After that, the heat input to the spacecraft structure by the cryocooler increases surrounding temperature and decreases cooling effectiveness, resulting in rising FPA temperatures. Increase in background during the course of 1.5 hours of lunar mapping was much less severe in the first month of mapping. At the midpoint of mapping, a major orbital correction maneuver was performed, expending fuel and reducing the thermal mass of the spacecraft platform. This allowed the optical bench temperature to rise more and the cryocooler heat sink temperature to similarly rise. It should be noted that the thermal design budget for the spacecraft included heat sources for limited NIR and LWIR camera usage, and that in operation, the on time for both cameras was 100% of orbit + more than 30 minutes cooldown before operation. The optical bench heating should be thought of as an over-taxing of a good design, not a failure of a design.

Table 3 summarizes key performance parameters and thermal conditions for the LWIR camera cryocoolers. The thermal environment was not particularly stressing when compared with the cryocooler rated temperature limits. These cameras were not heavily utilized prior to lunar orbit insertion on February 19, 1994. Thermal cycling during the roughly five hour lunar orbit period was the highest thermal stressing environment encountered.

Table 3.
Clementine LWIR camera cryocooler performance summary

Parameter	Value
Total cooler run time	670 hrs
Total number of on/off cycles	359
FPA operating temperature (typical)	67 K to > 85 K
Maximum recorded cooler non-operating temperature	41.0°C
Maximum recorded cooler operating temperature during imaging (FPA temperature at this condition in parenthesis)	37.2°C (82.9 K)
Minimum recorded cooler operating temperature during imaging (FPA temperature at this condition in parenthesis)	1.2 °C (80.6 K)
Minimum recorded cooler non-operating temperature	-22.1°C
Minimum recorded FPA temperature	66.9 K

Fig. 6 depicts engineering data for the LWIR camera for lunar orbit 72. This is typical of the cryocooler performance, and the thermal environment seen by the LWIR camera during lunar mapping. Operating FPA temperature for this orbit varied from 81.4 K to 95.2 K over a 93 minute time period. The cooler temperature rose 44°C, starting at -10.4°C, during the 113 minutes that the cooler was powered on.

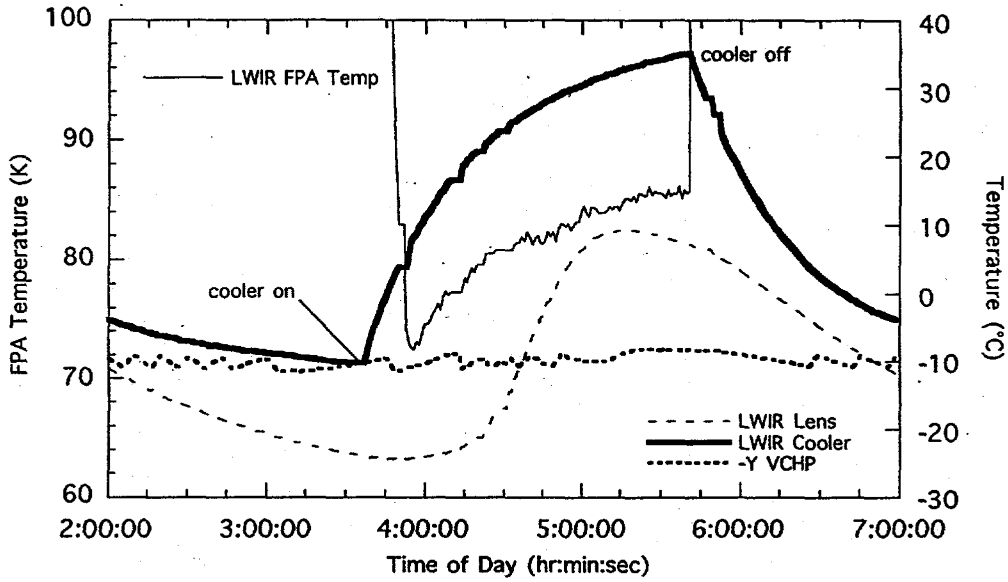


Figure 6. LWIR camera engnieering data for lunar orbit 72, 7 March 1994. The lack of slope change in cooler temperature is indicative of full-throttle, open-loop cooler operation. -Y VCHP, relatively constant at -10°C for this orbit, is the heat sink for the camera.

Camera currents, while undersampled, provided trend data on the cryocooler current draw. Fig. 7 illustrates the cryocooler current for the two cameras for orbit 72. Spacecraft bus voltage is shown for reference, noting that each IR camera was experimentally determined to provide consistent radiometric response for a bus voltage variation from 24 V to 36 V. Features of note are that the NIR cryocooler current does not hit the rail of the telemetry A/D converter except occassionally during the first 10 minutes of operation when the cryocooler is operating at full throttle during cooldown. The LWIR cryocooler shows very different behavior: the current quite often hits the 1.011 A upper rail. By comparison with other Clementine IR cameras, flight and prototype, this clearly indicates that the cryocooler is operating in the open-loop, full throttle mode at all times.

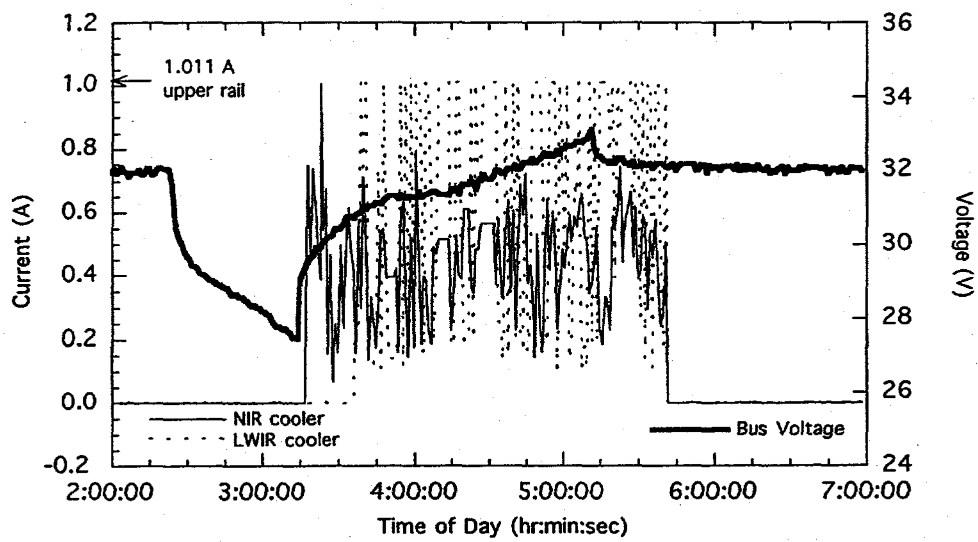


Figure 7. IR camera cryocooler currents for lunar orbit 72, 7 March1994.

Taken together, the large variation in indicated FPA temperature, the full throttle operation of the cryocooler from current readings, and the lack of a knee in the cryocooler temperature after 10 to 20 minutes, the LWIR cryocooler clearly was not operating to a set FPA temperature value. This is believed to be caused by a ground difference between the H-10 controller electronics and the FPA temperature sense diode.

Further discussions concerning the Clementine LWIR, and NIR, cryocoolers are presented in Ref [4].

LESSONS LEARNED

While the LWIR camera performed well throughout the life of the mission, a study of the images provided informatino on performance that could be improved showed a few features that could be improved, given adequate time and budget and use of today's technology. The end product of the LWIR sensor is images. The S/N and absolute accuracy of interpretation possible from the camera is the criteria for success. Several design features have been identified that have degraded the ultimate performance limit of the sensor.

During camera integration to the spacecraft, we found that the LWIR DC-DC converters were not capable of supplying the current required to the cryocooler to get to the desired FPA operating temperature. in our attempt to resolve this, power for the LWIR was supplied to both the signal conditioning electronics and the cryocooler through a linear regulator (stepping spacecraft 30 Vdc down to 22 Vdc) instead of the intended DC-DC converters. In hind sight, implementation of the linear regulators was not a good choice because this regulator placed excess noise on the Hybrid-10 FPA temperature feedback signal.

The first design feature that could be improved is the FPA temperature control. The net result was FPA temperature followed the cryocooler heat reject temperature. This occured because the Ricor Hybrid-10 control electronics were not properly integrated with the camera electronics in the redefined camera operating environment (see preceeding paragraph). This resulted in the cryocooler operating in an open-throttle mode at all times. Proper integration did not occur because there was inadequate time to do so. This time dearth occured due to a fixed delivery date for this camera to the spacecraft combined with mechanical failures of the dewar cold shield in random vibration testing. The control problems were caused in part by the H-10 electronics ground floating on the power leads for the motor. The FPA diode temperature sensor current source was referenced to H-10 ground, which generated an AC noise signal in the control circuitry. A ground difference circuit was designed and in test when time ran out, and we did not implement this fix.

A second design feature which would impact image noise would be the use of separate DC-DC converters for the cryocooler and the signal conditioning electronics. In the Clementine embodiment the FPA outputs were synchronized with the cryocooler AC signal (to send FPA data out when the cryocooler was off) to reduce the total noise, but this solution was not perfect. Additional noise occured on every 8th pixel as a result of this synchronization. Separation of power conditioning would reduce noise.

A third design feature that could be improved is the non-uniformity of the raw image from the array. Due to time constraints and the limited availability of radiation resistant memory, only 16-bits of memory were available for storing non-uniformity correction data on the camera. With an MCT array, with up to 100% dark current variation (1-σ), and tens of percents responsivity variation, both of which were high-frequency in nature, data compression will flatten out valid (recoverable) pixel variations. Allowable data compression can be improved (and data gathering throughput increased) if the non-uniformity correction of the raw image is improved.

The A/D provided by the camera is 8 bits, with variable gain and offset which increase the effective range of information to 13 bits- if the scene dynamic range is limited to 8 bits and the exposure settings can be correctly set apriori. In practice, the useful scene content was limited to 7-bits due to uncertainty in image radiance. This could have been improved by providing more A/D information, and compressing before transmission to limit the scene to 8 (or more) bits before downlink. A second feature of the electronic gain control was extreme noise. Studies of the companion NIR camera showed that the electronic gain switching increased FPA noise by up to a factor of 30. While this was not explicitly tested for the LWIR camera, it is believed to be a similar problem.

A general improvement, should another mission be flown, would be to design custom optics for the specific application. The Clementine LWIR camera included a large aperture that was later apertured down (effectively) with the cold filter. Improvements in performance might be possible, such as elimination of one relay path which reduces thermal emission, if a simplifcation of the optical design is permitted.

CONCLUSIONS

The LWIR camera provided capable imaging of the moon in contiguous north-south strips which exceeded the pre-flight duty requirements. The small, low power unit provided valuable data for its use in a space environment. The LWIR camera system developed and produced by LLNL and Amber Engineering for the Clementine mission represented a significant technical challenge, not the least of which was the tight development, testing and delivery schedule for the systems. A total of eleven LWIR and NIR cameras were produced, and two were successfully flown on the mission. Space flight qualification vibration tests performed on prototype units identified mechanical deficiencies which were resolved in real time. System integration testing identified other issues which were resolved on-the-spot so as to maintain overall program schedule.

ACKNOWLEDGEMENTS

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