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Near-infrared camera for the *Clementine* mission

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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 near-infrared (NIR) multi-spectral camera, one of two workhorse lunar mapping cameras (the other being the UV/visible camera), provided ~200 m spatial resolution at 400 km periselene, and a 39 km across-track swath. This 1.9 kg infrared camera using a 256 x 256 InSb FPA viewed reflected solar illumination from the lunar surface and lunar horizon in the 1 to 3 μm wavelength region, extending lunar imagery and mineralogy studies into the near infrared.

A description of this light-weight, low power NIR 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, Clementine NIR camera, Lunar Imagery, Imaging Sensors, Indium Antimonide, Ricor Cryocooler.

INTRODUCTION

The Clementine camera is a modification of earlier NIR cameras developed under the then Strategic Defense Initiative (SDI) program for Brilliant Pebbles. A 256 x 256 pixel InSb FPA with variable gain and offset electronics, a filter wheel, and a long-life, low-power cryocooler were transfered from earlier camera versions and combined with a modified optical design to tune the NIR sensor for the lunar mapping mission. Six spectral bands were chosen to enhance differences in spectral albedo measurements between the known lunar material minerals, providing the most accurate mapping base possible. Optics were designed for maximum throughput to allow adequate S/N with the narrow spectral bands chosen. In order to survive this planned 7-month long mission, the NIR camera incorporated radiation-resistant materials and adhered to applicable design practices.

In addition to generating a data set for lunar mapping, the NIR 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.

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NIR CAMERA MISSION GOALS

The primary purpose of the Clementine mission was to flight qualify and test in a space environment 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 minerological mapping of 100% coverage of the lunar surface (which was successfully completed), and spectral studies of the asteroid geographos (which was not completed). Studies of radiation environment effects, camera noise under spacecraft platform control, and all lifetime issues were performed.

DESCRIPTION

The Near Infrared (NIR) camera, shown in Fig. 1, used a 1992 state-of-the-art Amber 256 x 256 Indium Antimonide (InSb) FPA for imaging between 1 and 3 µm. Wavelength range was controlled by a combination of a cold filter, using an interference coating in combination with an absorptive substrate, and narrow bandpass ("warm") filters using exclusively interference filters for band blocking located in the filter wheel module. Detailed discussions of the signal conditioning electronics, optics, crycooler, interface, usage, and environmental requirements follow. Camera performance specifications are summarized in Table 1. A functional block diagram is shown in Fig. 2.

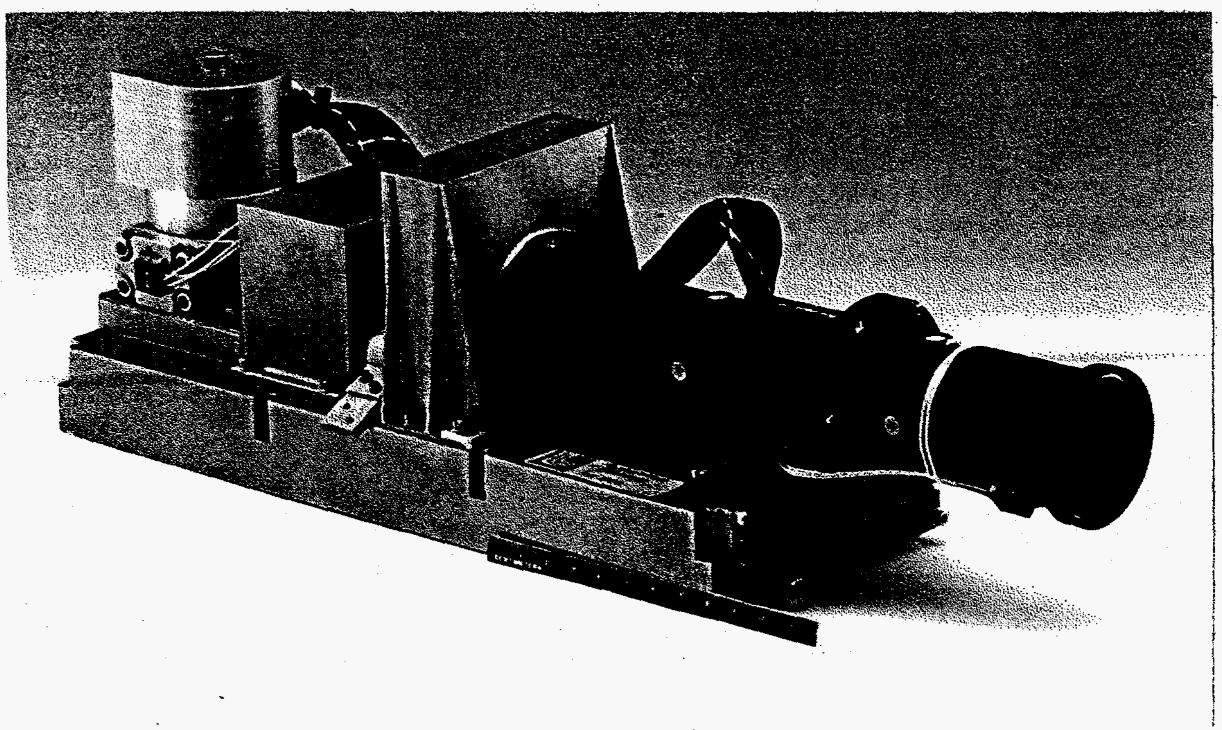


Figure 1. Clementine near-infrared camera.

Table 1. Clementine NIR camera Specifications.

Focal Plane Array	
Type	PV InSb (Amber)
Pixel format	256 x 256
Pixel size	38 x 38 microns
Non-operable pixels	≤ 0.5%
FPA operating temp	70 K
Optics	
Equivalent clear aperture	29 mm
Effective focal length	96 cm
Cold stop	F/3.33, 6.00 mm aperture
Cold shield efficiency	100%
Imaging	
Field of view	5.6° x 5.6°
Pixel IFOV	400 x 400 μrad
Point spread	≥ 50% energy in 30 μm slit
Warm filters	1.10 μm CW (± 0.03 μm BW), 1.25 (± 0.03), 1.50 (± 0.03), 2.00 (± 0.03), 2.60 (± 0.03), 2.69 (± 0.06)
Temporal noise	< 2400 e^- rms @ $\tau \leq 57$ ms
FPA well capacity	11.7 million electrons
Camera Electronics	
A/D resolution	8 bits
Frame rate (single frame mode)	7.1 Hz
Integration times	11, 33, 57 and 95 ms
Digitization gain	27 settings from 0.5 to 32.5 (1,250 to 45,700 electrons/count)
Offset control	8 bits; 8 bits = full well
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
Filter Wheel System	
Type	6 position, 90° stepper motor driven, Hall effect position sensors,
Step and settle time	≤ 250 ms
Position repeatability	≤ 10 mr
Power	0.15 W quiescent, 11.0 W stepping
Mechanical	
Mass	1.92 kg
Envelope	10.4 cm x 11.5 cm x 36.5 cm long

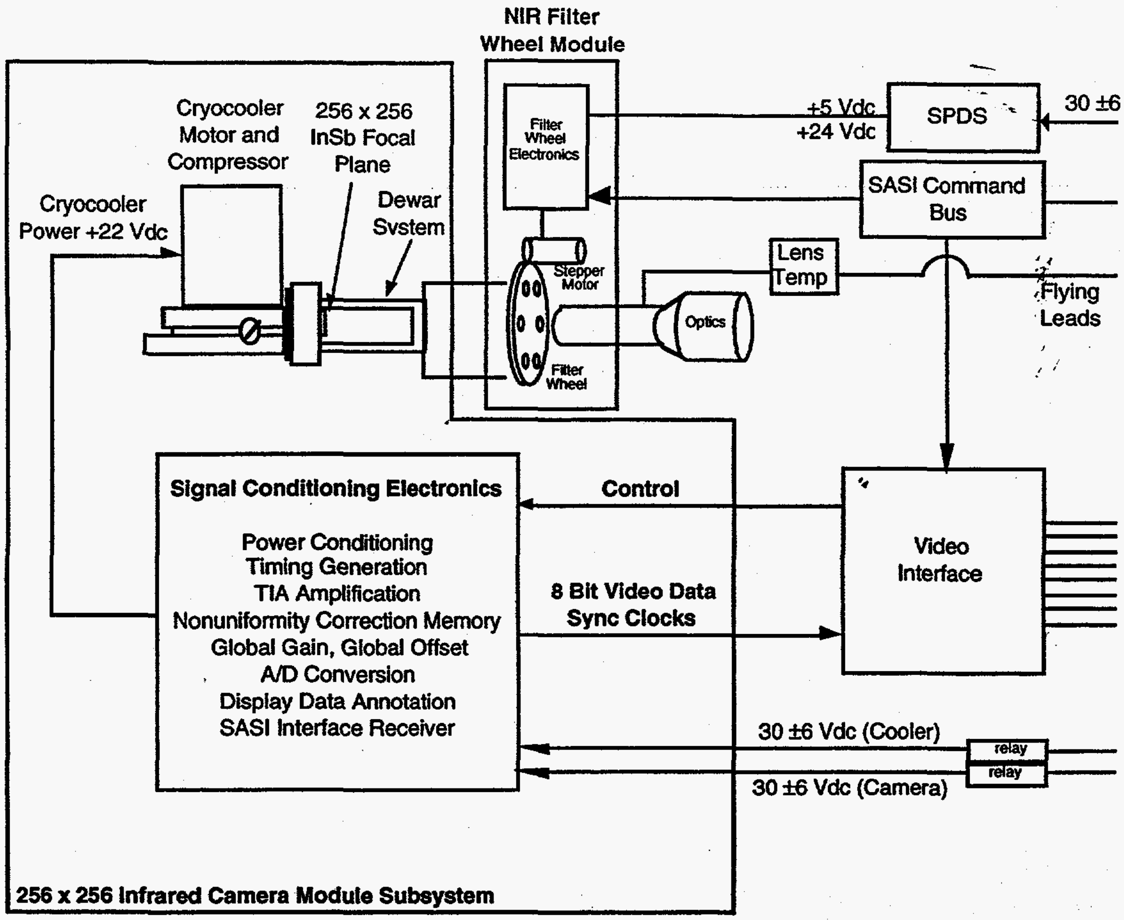


Figure 2. Clementine NIR camera functional block diagram.

Optical System

The optical characteristics of the NIR camera have been previously summarized in table 1. The optical assembly is shown in Fig. 3. The 5.6 x 5.6° field of view was sized to match the UV/Visible and allow 100% mapping coveregae of the lunar surface with a minimum number of orbits. Several performance requirements drove the optical design to its present configuration. These are, in roughly the order of importance, 1) spectral range from 1.0 to 2.8 μm, 2) field of view, 3) passive athermalization, and 4) 100% efficient cold shielding. These combined requirements pointed the design to a catadioptric configuration, using only ZnSe refractive components. Placing the bulk of the power on mirror elements allowed better athermalization and greatly reduced chromatic aberrations. The F/number of 3.33 represents a 29 mm entrance pupil diameter and a 96 mm focal length. The entrance pupil was maximized, as constrained by image quality, to allow the sensor to collect the strongest signal possible. Effective emissivity of the optics, coming from the low emissivity optics/coatings and black anodized internal lens housing, was minimal.

The filters used in the camera provided 10^{-4} out of band rejection. This was set by limiting out of band light to less than 1% of the in-band signal over typical scene spectral radiance distributions.

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.

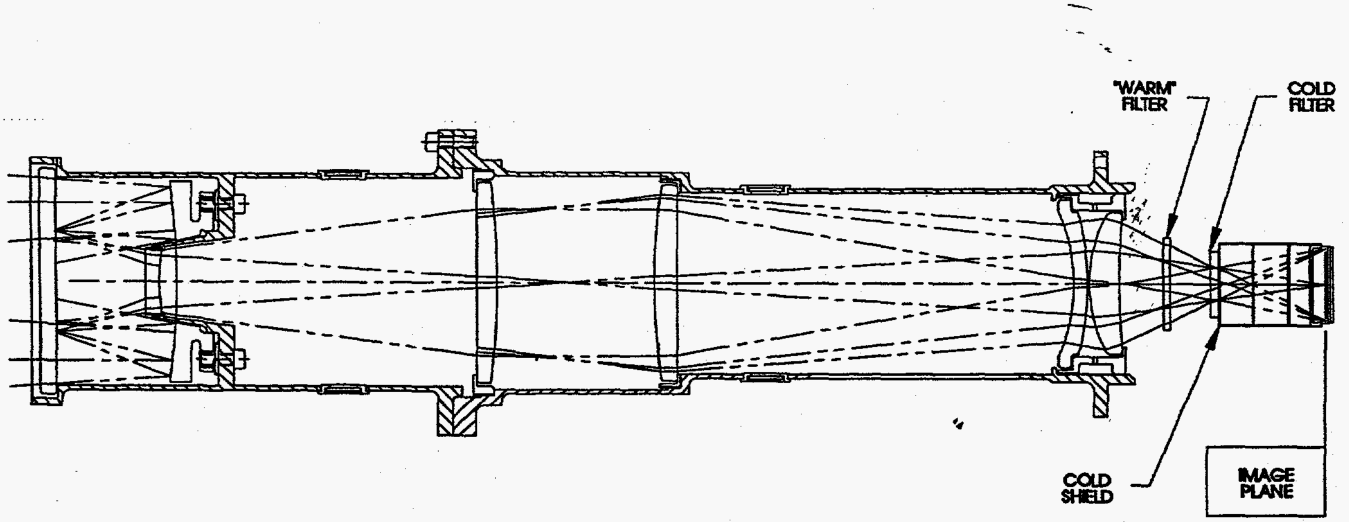


Figure 3. Optical system for the Clementine NIR camera.

Signal Conditioning Electronics

A single circuit board was designed for use with either the 256 x 256 pixel (single channel) NIR focal plane as well as the 128 x 128 (2 channel) LWIR focal plane array. 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 65K to 77K) 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 257th 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.

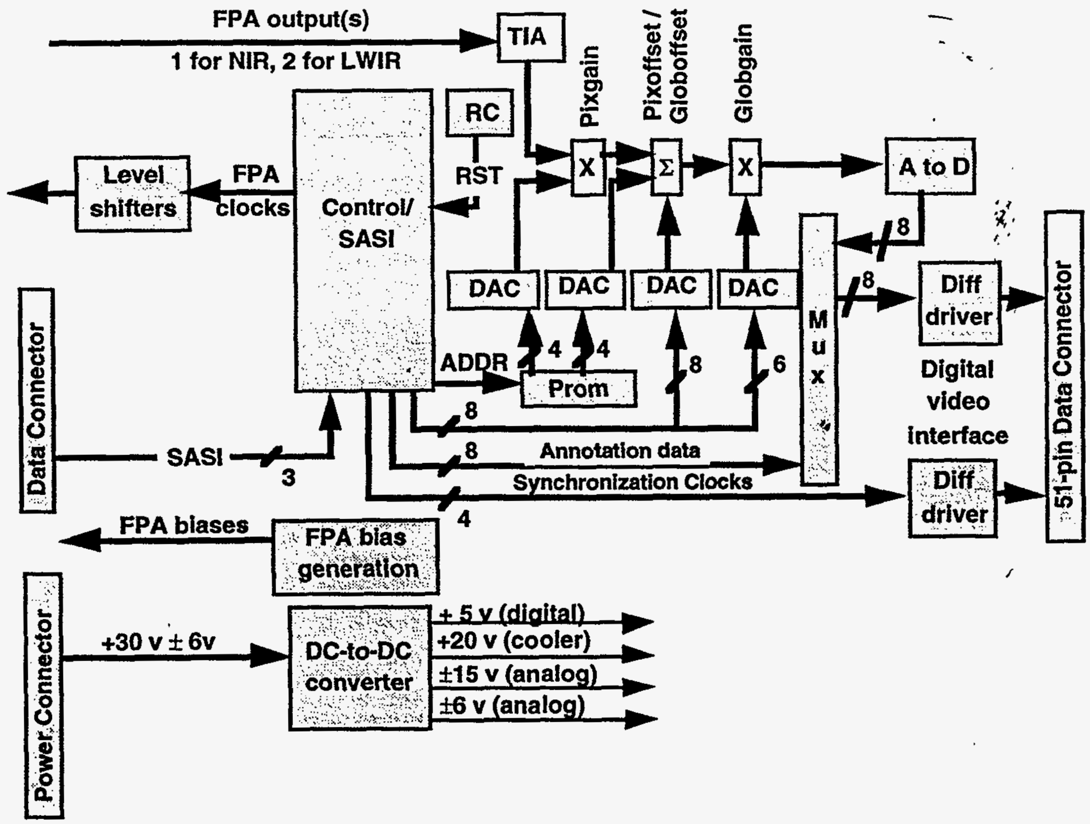


Figure 4. A detailed block diagram shows all necessary power conditioning, camera control and spacecraft interface electronics that were included on a single circuit board. Pixel gain and offset correction as well as global gain and offset control are implemented in the analog domain.

Sensor Engines

Sensor engines, consisting of the InSb 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 InSb FPA operating in the NIR was 70 ± 0.5 K based on the desired radiometric performance goal for this camera.

NIR Camera Six-Position Filter Wheel System

Six (6) spectral bands are selectable from a filter wheel which is controlled through a serial-addressable synchronous interface (SASI). Six filter positions are available using a space-rated 90° No. 5 stepper motor geared at 6:1. A series of Hall Effect sensors for position determination, and a small electronics card for command and operation make up the balance of teh 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 programmable array. The filter position control board is a rigid printed circuit board with dual thermal planes. This system is modular and functionally separate from the imaging camera.

ENGINEERING HOUSEKEEPING DATA CHANNELS

Engineering housekeeping data to track the operation and performance of each cryocooler included FPA temperature, cryocooler skin temperature, cryocooler current and spacecraft bus voltage. FPA Bias voltage, intended to track the effects of radiation on FPA responsivity, was also monitored and is a secondary indicator of the FPA temperature.

FPA temperature was measured with a 2N2222 base-emitter junction diode bonded to the motherboard of the dewar coldstack. The location of the diode results in a calculated temperature difference, between the motherboard and the FPA, of < 1 K for nominal imaging and operating conditions. Diodes were supplied with calibration curves. The diode signal was excited with 500 μA bias from the Hybrid-10 control electronics, then amplified through a gain stage to approximately 10.2 V full scale.

Cryocooler temperature was measured with a Fenwall LTN-11 thermistor bonded with Tra-Bond BA 2151 thermally conductive epoxy to the compressor on the compressor chamber flat. The thermistor was left exposed because the entire camera, except for the optics clear aperture, was wrapped in multi-layer insulation for radiative isolation. Thermistors were purchased with calibration curves.

Cryocooler current was measured as part of the camera 30 volt supply. Data was acquired by multiplexing the signal into the spacecraft Engineering Housekeeping Data. This signal was highly undersampled, sampled once every 16 seconds, compared with the cooler commutating frequncy of roughly 30 Hz. Consequently, cooler current data can only show a trend instead of average values.

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.

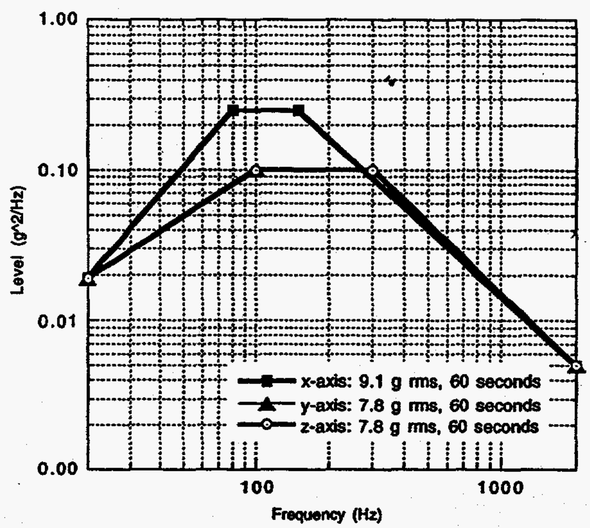
The camera required eight No. 4-40 bolts to attach it to the spacecraft. Two 1100-0 aluminum thermal straps were used for interfacing to the spacecraft thermal management system (attached to the cryocooler stator and to the stepper motor body). There were both selectable analog and digital signals to provide FPA temperature and Bias voltage data. Fenwall LTN-11 thermistors monitored the cryocooler and lens temperatures. 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 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 (specifically on the InSb FPA), random vibration, thermal cycling, thermal vacuum and electronic burn-in. Table 2 summarizes the test environments.

Table 2. Clementine NIR 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 Actual)	
Thermal Cycling	-30°C to 20°C, six cycles
Thermal Vacuum	by similarity with qualificaion unit, -20°C to 20°C
Electronic Burn-in	≥ 300 hrs

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's error. 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.

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. The final calibration is expected to be better than 5%.

CLEMENTINE MISSION DATA

The NIR 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 NIR 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. Near the poles, where range to the moon was on the order of 1000 km, the time between the sets of 6-filter position data cubes were on the order of 20 minutes; near the equator (periselene), the frequency increased to roughly 4 minutes between data cubes. Data was generally compressed at a typical ratio of 7:1, varying slightly with scene content. The compression was adjusted to give less than 1/4 count rms difference between an uncompressed (original) download file and a compressed/decompressed image, as evaluated on typical lunar scenes at the beginning of the orbit. It is worth noting that the non-uniformity of the focal plane, compared to the performance of the UV/Visible camera, which had virtually identical scene structure, reduced the allowable data compression due to the residual high-frequency image structure. A typical NIR lunar image is shown in Fig. 5.

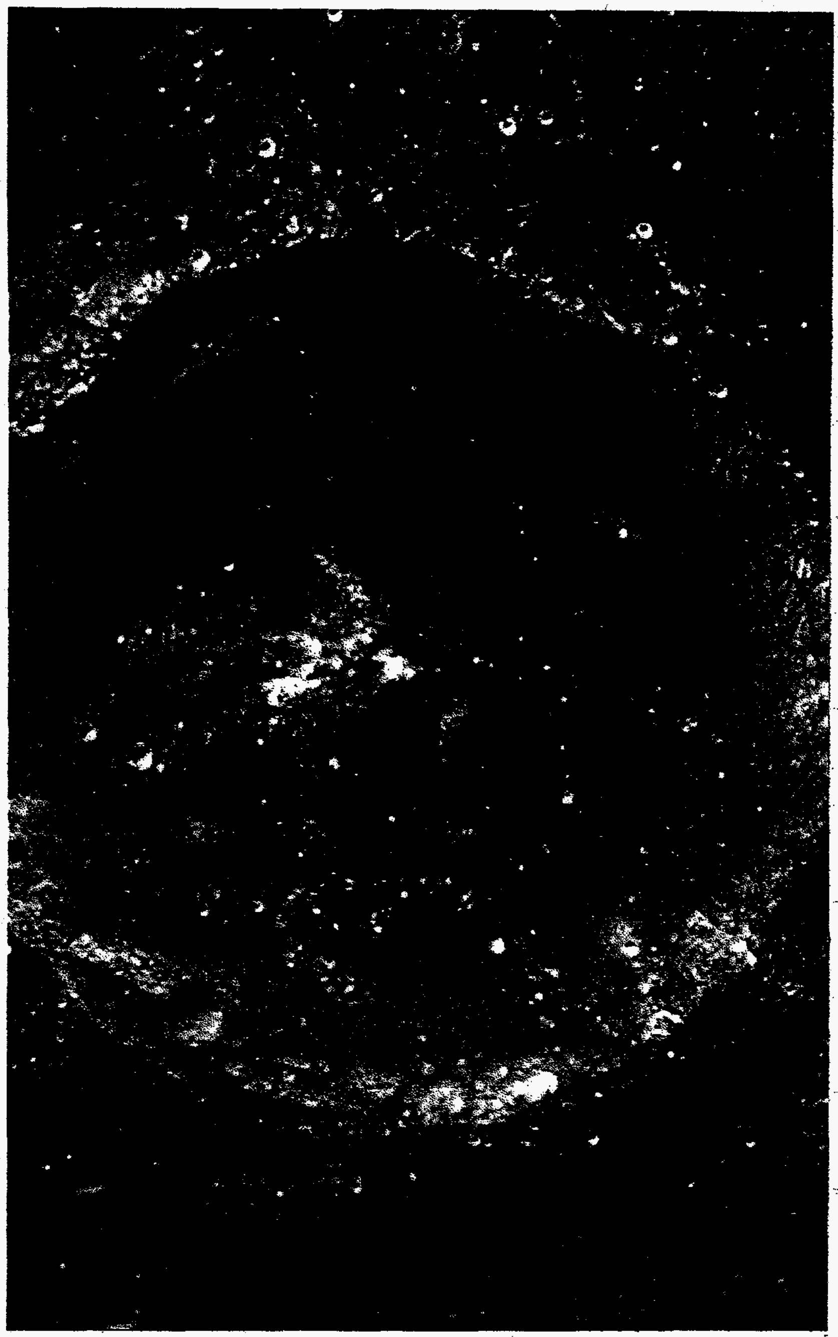


Figure 5. This view of the Rydberg crater was captured by the NIR camera on March 6, 1994 from an altitude of 460 km. The crater size is roughly 35 km diamter. In this composite, North is up.

Camera integration time, offset, and gain controls were set by a spacecraft control file, which switched instructions every 10° latitude. Near the equator, the NIR camera was operated at the shortest integration time and a very low (i.e. 2.5X) gain to fill the A/D wells appropriately. Near the poles, where lunar radiance dropped off severely, the integration time was increased to 57 msec and the gain was also increased slightly.

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 NIR 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 was equal to the total signal seen at the extreme polar regions. Cooling of the NIR to 10% of polar radiance signal took 45 minutes for the flight sensor. 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 NIR camera cryocooler during the Clementine mission. 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 NIR camera cryocoolers performance summary.

Parameter	**NIR**
Total cooler run time	840 hrs
Total number of on/off cycles	361
FPA operating temperature (typical)	70.3 ± 0.46 K
Maximum recorded cooler non-operating temperature	38.2°C
Maximum recorded cooler operating temperature during imaging (FPA temperature at this condition in parenthesis)	26.8°C (70.6 K)
Minimum recorded cooler operating temperature during imaging (FPA temperature at this condition in parenthesis)	-8.5°C (71.1K)
Minimum recorded cooler non-operating temperature	-23.7°C
Minimum recorded FPA temperature	66.2 K

Fig. 6 shows the NIR camera engineering data for lunar orbit 295. This is typical of the cryocooler performance, and the thermal environment encountered by the NIR camera during lunar mapping. FPA temperature for this orbit operated at a mean of 70.0 ± 0.47 K. The sun angle at the equator during this orbit was 25.9°. By comparison, orbit 72, with a sun angle of 16.3°, produced a slightly higher FPA temperature at 70.3 ± 0.46 K. The cooler temperature in Fig. 6 is typical of the NIR operation. A knee in the cooler temperature always occured. This knee indicates that the cooler had gone into the control mode, and the FPA is at its operating temperature. NIR cooldown times were typically less than 9 minutes. A more detailed presentation of Clementine cryocooler performance is given in Ref [4].

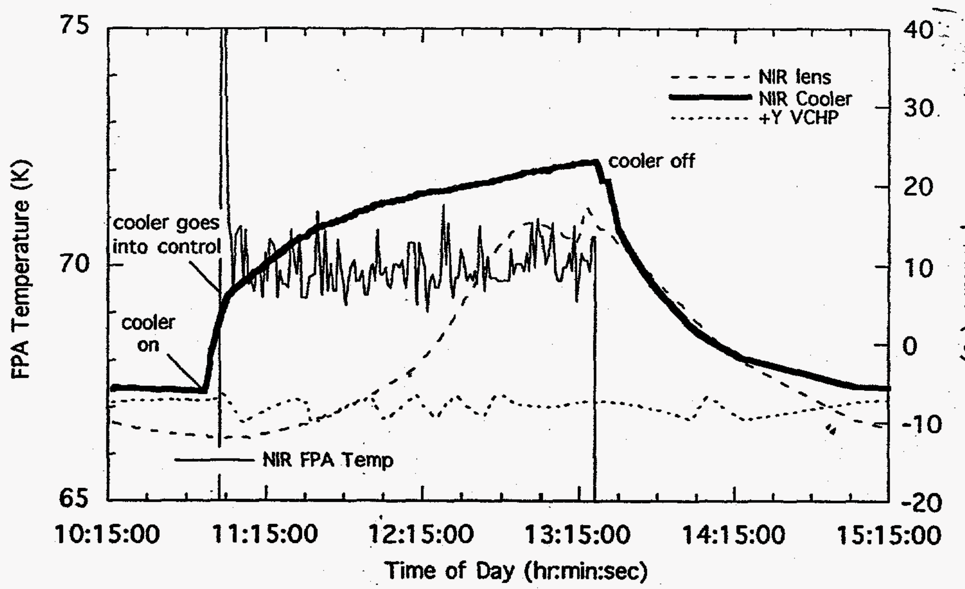


Figure 6. NIR camera engineering data for lunar orbit 295, 22 April 1994. +Y variable conductance heat pipe (VCHP) is the thermal sink for the camera. Aposelene occurs at the beginning and end of the time scale shown.

LESSONS LEARNED

While the NIR camera performed well throughout the life of the mission, a study of the images showed a few features that could be improved, given adequate time and budget and using of today's technology. The end product of the NIR 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.

The first design feaure that could be improved is the thermal contacting of the cold filter to the cryocooler. The FPA temperature of the array consistently reached 70 K and stabilized within 10 minutes of powering on the cryocooler. The dark signal seen in space images, however, saturates the camera for another 5 minutes, then fell in an exponentially decreasing curve, still yielding significant signals 45 minutes after cryocooler turn on. This is believed to be the result of poor thermal contact between the cold filter and the cold finger due to a partially torn DC 93-500 bond line. Future designs would place the cold filter closer to the focal plane and would decrease the thermal path between the two items.

A second design feature that could be improved is the non-uniformity of the raw image off the array. Due to time constraints and the limited availability of radiation resistant memory, only 2-bits of memory were available for saving non-uniformity correction data. With an InSb array, with up to 11% dark current variation (1-sigma), and several percent 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 excess noise. Readout noise directly off the FPA tested with a standard 12-bit test set showed readout noise of 200 electrons rms. In practice, up to 30 times that noise value was seen, with noise differing (disproportionately to gain) when different gain settings are selected. This is believed to come from the resistor switching network that is accessed with gain control state. The open resistors act as noise pick ups. This, too, would be elimnated with a 12-bit fixed A/D design.

A third 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 less than perfect. Additional noise occured on every 8th pixel as a result of this synchronization. Separation of power conditioning would reduce noise.

CONCLUSIONS

The NIR camera provided the full complement of images desired for mineral typing the moon's surface. The NIR (and 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 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 potential issues which were resolved on-the-spot so as to maintain overall program schedule.

The excellent working relationship which existed between the development teams at Amber and the Lawrence Livermore National Laboratory were directly responsible for the success of these cameras during the Clementine mission. Such cooperation existed at all levels throughout the execution of this mission; to its credit, the mission collected the most complete database of multi-spectral lunar imagery in history.

ACKNOWLEDGEMENTS

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