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Star Tracker Stellar Compass
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. Two star stracker stellar compasses (star tracker camera + stellar compass software) were included on the spacecraft, serving a primary function of providing angle updates to the guidance and navigation system. These cameras served a secondary function by providing a wide field of view imaging capability for lunar horizon glow and other dark-side imaging data. This 290 g camera using a 576 x 384 FPA and a 17 mm entrance pupil, detected and centroided stars as dim and dimmer than 4.5 m_V, providing rms pointing accuracy of better than 100 μrad pitch and yaw and 450 μrad roll.

A description of this light-weight, low power star tracker 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, Star Tracker Stellar Compass, Spacecraft Attitude Determination, Lunar Imagery.

INTRODUCTION

The Clementine flight unit star tracker is the latest model of the Ballistic Missile Defense Organization (BMDO), formerly SDIO, lineage wide-field-of-view star tracker camera designs. The star tracker focal plane, optics, and pointing algorithms were first demonstrated in 1987. Previous papers [1, 2] describe previous models, along with performance expectations. The Clementine vintage has improvements in radiation resistance, solar rejection baffles, low distortion fiber optics plate, and quaternion angle finding algorithms. With these improvements, the star tracker system was able to reliably determine quaternions throughout the life of the mission.

CLEMENTINE MISSION

The Clementine spacecraft was 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 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 [3, 4] provide good overviews and insight into utility of the Clementine data which has been analyzed.

STAR TRACKER 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. The star tracker camera was selected for the mission because it was a light-weight, medium accuracy star tracker, which was capable of meeting the pointing and navigation requirements of the Clementine flight plan. It served double-duty as a very wide field of view imager (for lunar horizon glow studies) and as a Cherenkov radiation detector with the aperture closed using extremely long integration times.

DESCRIPTION

The star tracker stellar compass, hardware shown in Fig. 1, consists of stellar compass software and the physical camera. The hardware consist of a lens, baffle, and a small camera module (consisting of the CCD, camera electronics, and housing). These are described in this section. Table 1 summarizes the camera technical specifications. A functional block diagram is shown in Fig. 2.

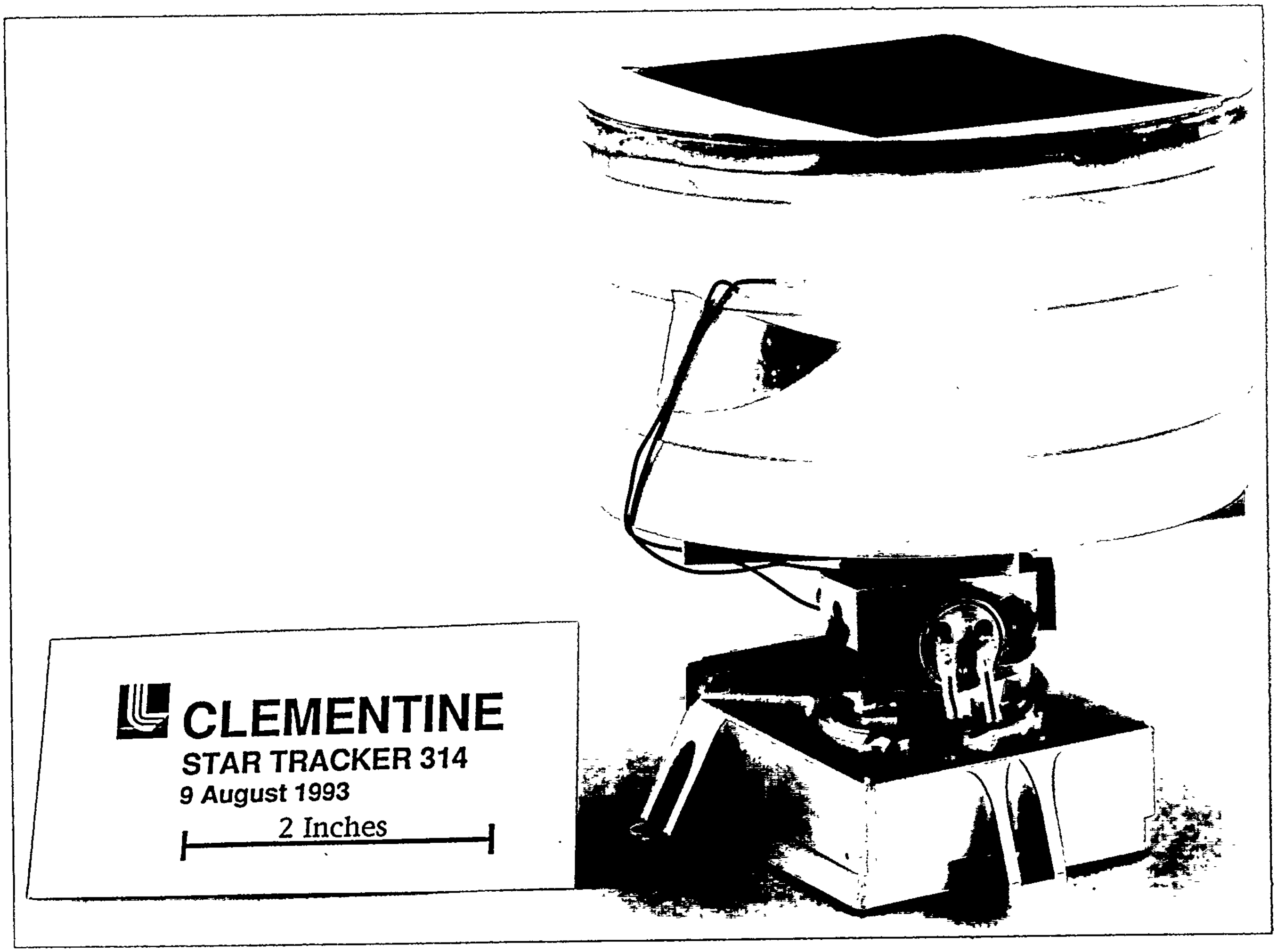


Fig. 1. Clementine star tracker camera.

Stellar Compass Software

The stellar compass software is a robust set of algorithms resistant to errors induced by noise and moderate amounts of scattered stray light. The major algorithm steps for the camera are:

- sweep each line for potential stars, using self-adjusting differential requirement
- perform blobifying routine to outline potential stars
- find peak pixel reading in each blob
- check blob shape against nominal stellar blur
- find local star background
- find local star centroid and mass
- order star masses
- take top (10) stars to triangulation, with selection weighting towards outer FPA pixels

Table 1. Star Tracker Camera Performance Characteristics.

Attribute	Characteristic
Focal Plane Arrays	
Type	Thomson TH7883-F02-01-B/T Si CCD - 0.4 to 1.1 microns Full Frame Device
Pixel Format	384 x 576
Array Size	8.83 x 13.25 mm
Pixel Size	23 x 23 microns
CCD Operating Temperature	10°C Maximum (Clementine spacecraft specific)
Optics	
Type	Concentric Refractive
Aperture	14.0 mm diameter.
Focal Length	17.5 mm
Speed	F/1.25
Imaging	
Spectral Range	0.4 to 1.1 microns
Array FOV	28.9° x 43.4°
IFOV	1.314 x 1.314 milli- radians
Point Spread	20%-40% of image blur energy in 23 μm square and >80% in 75 μm square
Noise Characteristics	< 90 electrons @ 20°C for 50 ms integration time. Dark current and dark signal non-uniformity are limiting for longer integration times.
Electronics	
A/D Resolution	8 bits
Frame Rate	<10 Hz
Readout Time	54.8 msec
Digitization	75, 150, 350 e^-/count
Readout Noise	60 e^- RMS
Integration Time	0.2-773 ms (typical ≈150 ms)
Offset Control	248 gray level offset; 5 bit control word; LSB = 8 gray levels
Average Power	
Camera	4.5 Watts
Lens Heater	≤ 1.95 Watts (50% duty cycle @36 v)
Physical	
Envelope	11.7 cm x 11.7 cm x 13.2 cm
Mass	290 g

- list triangles formed by star group
- match triangles to star atlas-derived triangles
- calculate quality of best match
- output match quality and quaternion for navigation use

A number of features that are seen in many high-accuracy star trackers, such as magnitude matching for each star after rough triangulation and "S"-curve correction of the centroid algorithm are not employed. Nor is distortion of the lens corrected on the as-built unit. Without these features, the centroiding algorithm, which is a simple mass-centroid calculation, will return up to 1/25 pixel error for some star center locations with respect to the focal plane. These features were not included because the accuracy of the star tracker was sufficient to meet mission requirements without the additonal algorithm steps.

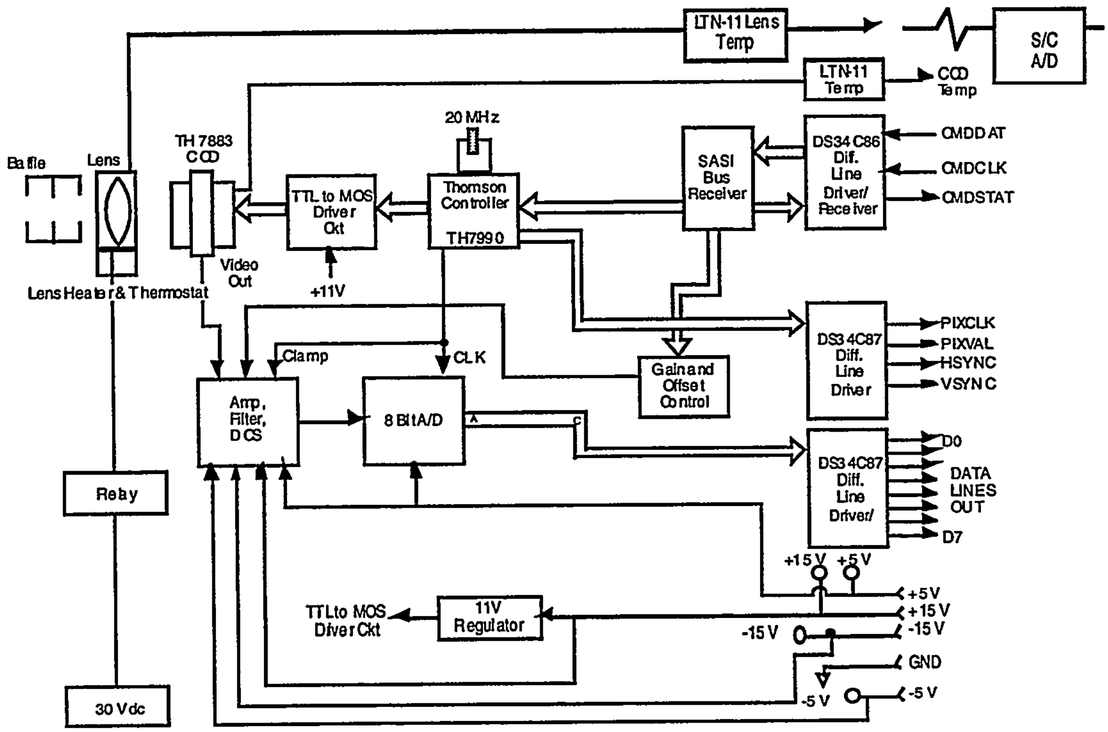


Fig. 2 Clementine star tracker camera functional block diagram.

Accuracy of the present star tracker is limited by the distortion pattern in the fiber optic faceplates located in the rear of the star tracker lens and on the focal plane array. Zero-shear faceplates were ordered for the Clementine built star tracker units, which decreased the rms distortion in the lens to roughly 200 μrad rms, with the peak distortion values at the edges of the focal plane (where stars are dimmer as imaged through the lens and are infrequently selected for triangle matching). With at least 5 stars required for a positive match, the contribution of a single star in the corner of the FPA to the overall pitch or yaw pointing error is reduced. Other sources of pointing error are noise influence on the mass centroiding error and the "S"curve error from the algorithm itself.

The end result of the algorithms implemented on the Clementine flight unit passed ground tests with <100 μrad rms pitch/yaw error and <450 μrad rms roll error. These tests were repeated zenith viewing throughout the night, with quaternions fit to an equatorial earth motion model. Zenith viewing reduces atmospheric refraction effects. Temporal noise in most star fields was on the order of 20 to 30 μrad rms, with occasional jumps in pointing quaternion seen as a star drifted onto (or off) a distorted fiber optic section. If a distortion correction algorithm were implemented, the noise level of 30 μrad pitch/yaw and 200 μrad roll would be achieved.

Perhaps the most unique features of this star tracker code are the adaptable threshold sweep, which allows operation even with degraded stray light and camera noise conditions. This algorithm group floats with background increase and with low frequency background changes across the field of view. Rows are processed left to right, and pixels that are N counts higher than the preceding neighbor are flagged as possible bright spots. The algorithm starts with a high threshold value (i.e. 10), and lowers the threshold by 1 count and re-scans the line until not more than 1 candidate star pixel is found. For example, if there are 3 pixels with a signal increase of 2 counts, no candidates will be found at 3 threshold, but 3 will be found at a 2 threshold. This causes the entire line to be discarded, since the noise is on the order of the brightest possible real star. Even if the pixel did pass the star test for this line, noise values would cause centroiding results to be inaccruate.

For Clementine, the on-board star atlas was a trimmed and adjusted version of the SAO catalog which included 464 stars. This set guaranteed that there would be 5 stars of m_V 4.5 or greater in the field of view at all times. The set was also adjusted to accomodate the color sensitivity of the CCD.

In flight, the star tracker camera reliably provided quaternion updates to the spacecraft throughout the life of the mission when the solar exclusion angle was respected, with 1 exception. Early in the mission, after stage separation, star matches were not achieved for a period of an hour. Later analysis of downlinked images showed that the 10 brightest blobs in the FPA were space debris resulting from the separation, which is a condition that was not expected in the default software.

Optical System

The star tracker lens was specified and built to have a 42° x 28° field of view. This sizing results in a pixel IFOV of 1.3 mrad, which is small enough to provide the requisite quaternion accuracy. The collection aperture of the lens is maximized for the greatest possible light gathering capability. At F/1.25, $m_V = 4.5$ G0 stars provide an integrated star signal that is 15 times the electronic noise from the focal plane. This level of signal gathering capability, matched with the wide field of view, ensures a 99.9% probability that 5 stars above minimum threshold will be available for the algorithm set for all possible quaternion pointing vectors. This allows the star tracker to handle the "lost in space" condition with a single star image frame and no other apriori knowledge of location.

To avoid chromatic aberrations that would shift star centroids with star color temperature at the edges of the field of view, and to maximize imaging F/number, a concentric optical design was adopted. For extension into a long-life space mission, only radiation resistance glass, including fiber optic faceplate material, was included in the optical path. Use of the radiation resistant material reduces transmission in the shorter wavelength regions of the CCD response, virtually blocking all light below 500 nm, however, for doses on the order of 10 KRad Si, the net transmission gains throughout the life of the mission compensate the early transmission loss.

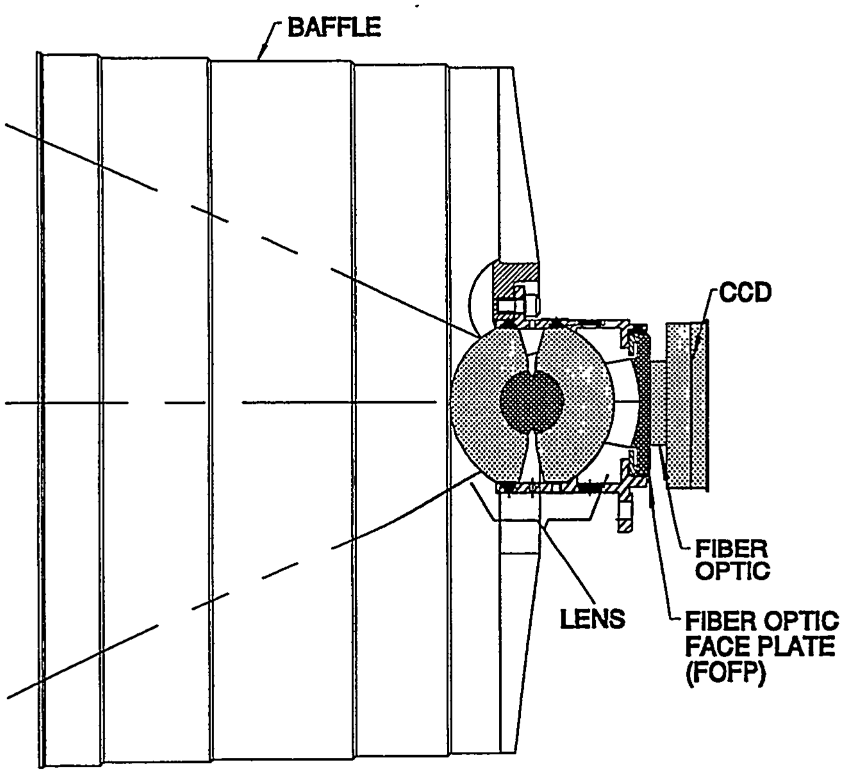


Figure 3. Star tracker optical system showing the image plane at the fiber optic face plate, the concentric lens elements and the single stage baffle.

Baffles

Small amounts of scattered sunlight can be much brighter than the image of the dim stars needed by the sensor for proper operation. (The sun is 12 to 13 orders of magnitude brighter than the stars used for navigation.) Without a baffle, operation would only be possible when the sun, solar-illuminated moon, and solar-illuminate earth are all behind the star tracker line of sight and not illuminating spacecraft structure in the forward hemisphere of the star tracker line of sight. A baffle was designed to allow operation with more general sun/earth/moon constraints.

Stray light reduction requirements for the camera were expressed in Point Source Transmittance (PST), which is defined as the ratio of flux reaching the FPA of a sensor to the flux at the aperture of the sensor. The design goal PST of the star tracker baffle/ lens opto-mechanical package was set at 10^{-7} PST, which yields a signal of 5 counts when the full solar illumination is incident (outside the rejection angle) on the star tracker camera at nominal integration time and gain settings.

Both flight star trackers were tested using a 1 kW quartz tungsten halogen lamp source for illumination. Testing was performed both outdoors and in the high bay assembly area for the Clementine camera. Both test areas had significant amounts of aerosol particulates, that contributed to the stray light readings. Aerosol magnitudes were typically $< 5 \times 10^{-7}$ equivalent PST, which made a correction of the aerosol signal to 10% accuracy well below the critical 10^{-7} PST testing goal. Scattering was in the range of 10^{-4} to 10^{-5} PST when the illumination source glanced off any structure (except baffle vanes) forward of the lens. The image saturated when the illumination source directly lighted optical surfaces. The results for the two flight units is given in Figs. 4 and 5, showing that the baffle blackening, vane sharpness, and dimensional layout combined to meet the stray light reduction goals.

The baffle was allowed to extend 3 inches past the star tracker lens vertex, and provided operation when the sun/earth/moon were outside a 65° x 80° angle exclusion zone. (The rectangular field of view is a result of rectangular baffle openings that pass the star tracker field of view.) Internal surfaces are coated with a MIL-F-495 Cu-black process on Ni-plated aluminum, which provided reflectance as low as industry standards Ball black and Martin black processes. Baffle construction, discussed later in this paper, was accomplished with adhesive.

Camera Electronics

The camera electronics are built around a Thomson TH7883 CCD, a Thomson TH7990 CCD controller and an Actel field programmable gate array (FPGA). The Actel FPGA controls operation of the TH7990 CCD controller and analog circuits (Gain, Offset and Double Correlated Sampling{DCS}) on the camera, generates video timing and additionally implements functions of the synchronous addressable serial interface (SASI) bus protocol receiver. The camera received commands from the Clementine Sensor Imaging Processor (SIP) via the SASI bus. The commands are received and processed by the Actel FPGA. The FPGA controls the operating modes of the camera by controlling the operating mode of the TH7990. The camera returns digitized video to the SIP. This is represented functionally in Fig. 6.

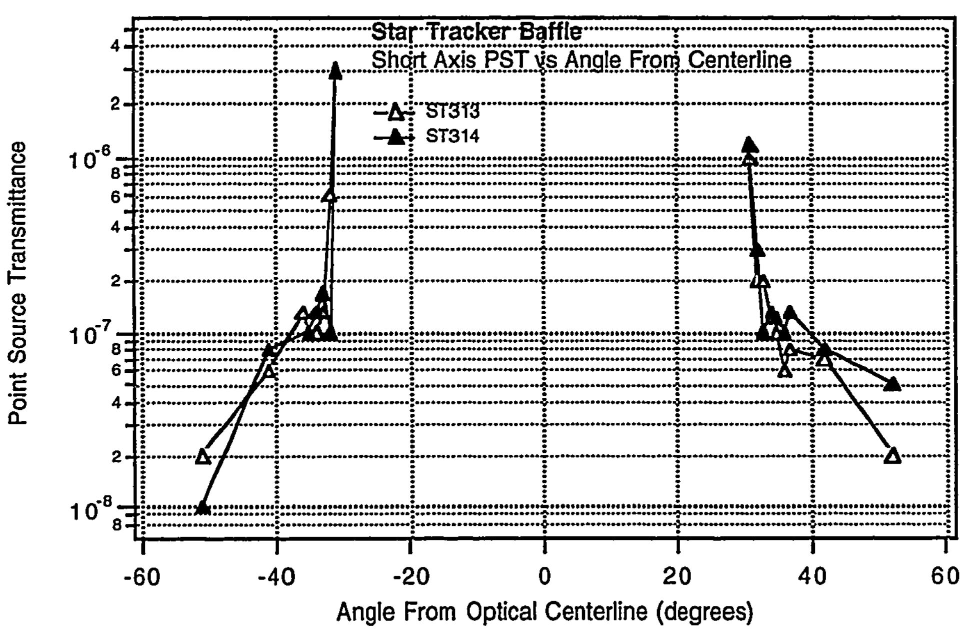


Figure 4. PST vs angle for the short axis of the flight star tracker cameras.

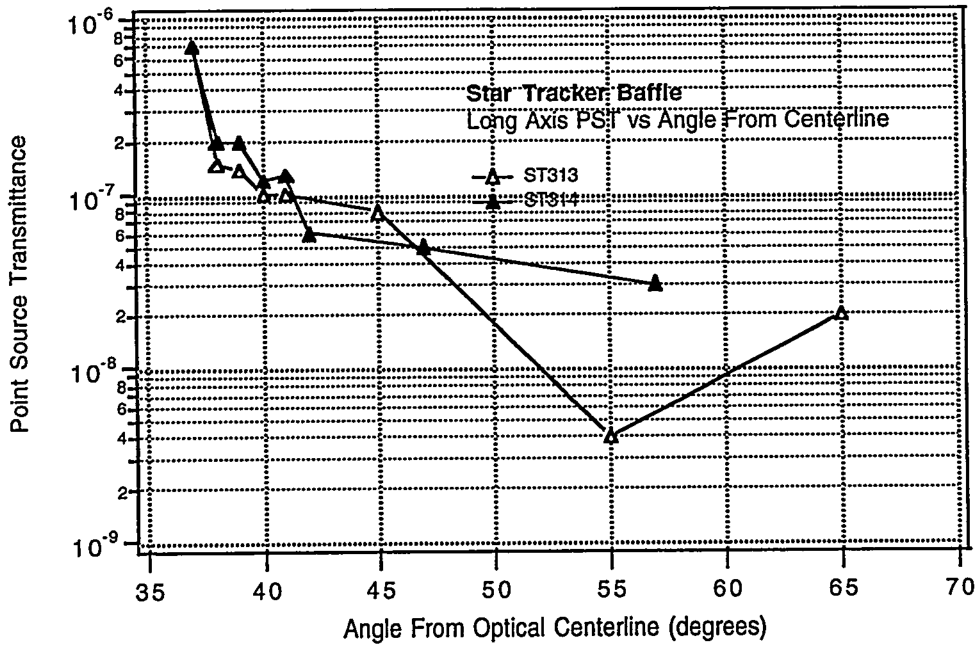


Figure 5. PST vs angle for the long axis of the flight star tracker cameras.

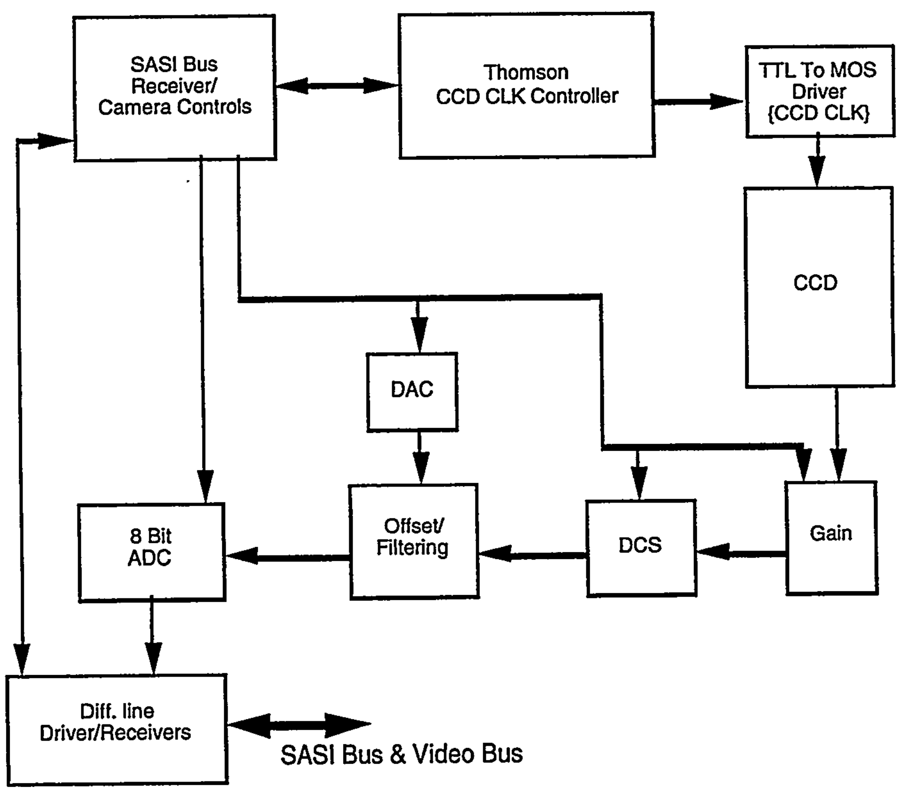


Figure 6. Star tracker camera electronics functional block diagram.

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.

The camera has two modes of integration control, precision integration control or SASI control. The mode is selected by setting the control bit (BIT 3 or parameter ID = 0) either HI for precision control or LOW for SASI control. If precision integration control is selected, 13 bits of integration data must be loaded into the command data registers at parameter ID 2 and 3 with bit 4 of the command data register at ID 3 being the MSB. Integration time in this mode equals (n+1) * 94.4 µseconds. The minimum acceptable n is 1, resulting in a minimum integration time for the star tracker of 188.8 µseconds. In the SASI control mode, integration is initiated by bringing the control bit (bit 0 of the parameter ID = 1) LOW. The control bit must be LOW for at least 100 µseconds. Readout is initiated by bringing the same bit HI. In the precision control mode, integration is initiated by a HI to LOW transition of the same control bit (bit 0 at parameter ID = 1). Readout will occur automatically after the pre-set integration time. The control bit must be returned HI before initiating the next integration cycle and left HI for at least 100 µseconds.

In the analog domain, the output of the CCD is buffered through an emitter-follower before global gain is applied. Camera gain is selected by setting one and only one of the gain control bits (bits 4-6 at parameter ID = 0) HI which switches a gain resistor. The camera has three gain setting of 350 e^-/bit ,150 e^-/bit and 75 e^-/bit. After global gain is applied, DCS is applied. Gain is applied to the signal before the DCS so as not to introduce excess noise to signal which would then be amplified. Timing for the DCS is achieved in an Actel FPGA. Offset is applied to the signal after DCS. Camera offset is selected by setting a 5 bit control word (bits 0-4 at parameter ID = 5) which is sent to a digital to analog converter (DAC). One LSB equals an offset of 8 gray levels. The maximum offset equals 248 gray levels. After offset the signal is converted to digital value by the flash analog to digital converter.

Camera Construction

The measured mass of the two Clementine flight star tracker cameras was 280 grams and 286 grams. The camera consisted of a camera module, lens assembly and light baffle. The camera module, the core unit utilized on this camera and the Clementine UV/Visible and HiRes cameras, contained a Thomson CSF 7883 CCD and a flexible printed wiring assembly (PWA). The lens assembly consisted of radiation-resistant Cerium-doped glass, aluminum housing and a thermostatically controlled Nichrome lens heater. The light baffle is a single stage device discussed earlier. This camera was designed to survive a 19.8 g rms, 60 second duration launch during launch aboard a Titan II G launch vehicle, and operate in space for the seven month duration Clementine mission.

Fig. 7 depicts the camera module. The PWA has three rigid sections (main, CCD and connector) where electronic components are mounted. These sections are connected by flexible lengths which allow the PWA to be folded over on itself. The main section contains most of the components and has it's thermal planes at the four corners exposed on both sides. These corners are clamped between the two pieces of the camera module for structural support and heat transport from the board. The space between the two camera parts at these corners is custom adjusted based on PWA thickness measurements so there is a 0.0005 ± 0.0001 inch compression of the PWA corners. This compression insures adequate contact pressure for heat transfer while maintaining the structural integrity of the printed wiring board.

The PWA is folded so that the CCD area is located beneath a tongue in the camera housing. This metal tongue is situated between the CCD and the CCD section of the PWA. Compliant thermal shims are located at the two interfaces. The CCD and the PWA are pressed tightly against this metal tongue with a metal retainer and No 2-56 fastners to thermally sink the CCD.

The main mechanical structure provides a precision surface for referencing to the lens housing via a spacer. The CCD in turn is aligned to the fiber optic faceplate (FOFP) at the back of the lens, and bonded to this FOFP with a curing, transmissive optical couplant. The focus spacer is custom-lapped to the finished height to within 0.0002 inches total indicated runout to insure parallelism. Further, a 0.0003 ± 0.0001 inch gap between the FOFP and the CCD face is achieved. This gap is filled with Dow Corning 93-500 optical couplant, cementing the lens to the CCD.

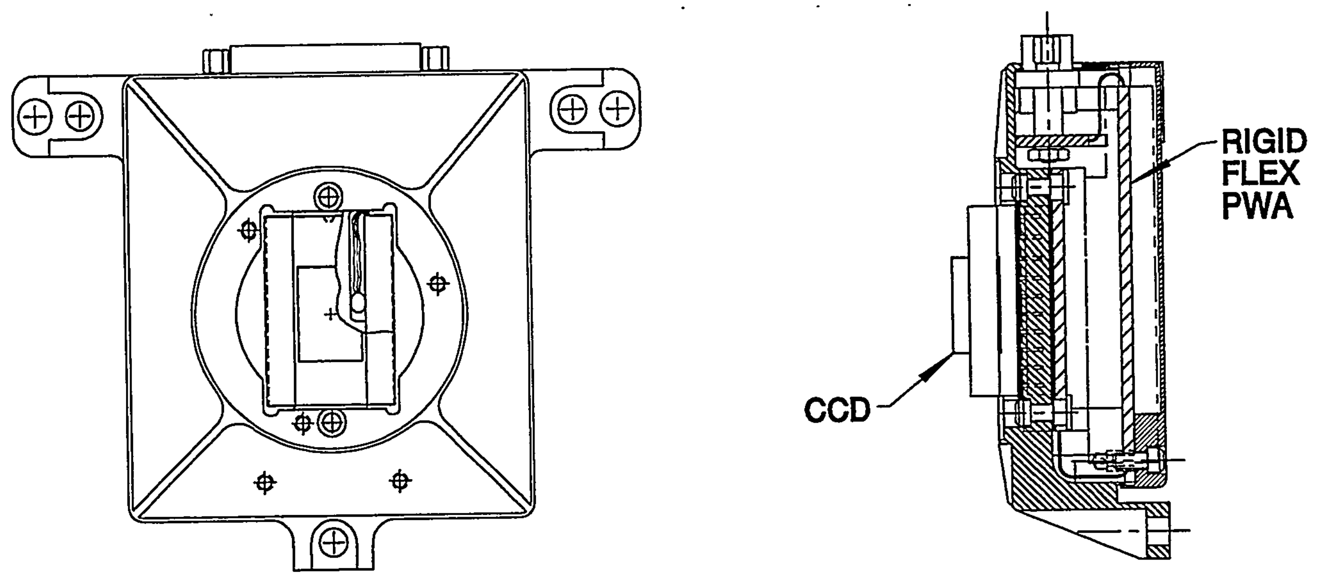


Figure 7. Camera module used for the star tracker camera.

Heat is transported from the components, the printed wiring board (PWB), through the aluminum housing and to the spacecraft's camera thermal management system. Hot electronic parts use thermal grease between the part and the PWB. The PWB is designed with two 1-oz thermal planes near the outer surface of both board sides. Further, thermal vias are located under expected hot components. The camera housing and end cover have integral heat paths with specific sections sized for low thermal resistance. A separate path for heat generated by the CCD is provided with use of an Al 1100-0 thermal strap, to insure that the temperature gradient between the CCD and camera cold plate is minimized. The flexible CCD thermal strap was fastened at the outside of the camera housing and then directly to the camera's heat pipe. Heat from the electronics is removed at the three mouning feet, and at the four corners of the camera's end cover. At all part interfaces (e.g. PWA to camera housing) a thin layer of Dow Corning 340 thermal grease is used to minimize thermal resistance.

The baffle is shown as part of Fig 1. All material is copper oxide black Al 7075. The baffle is fabricated by machining the cylinder with support steps for the vanes, and machining the 0.010" thick vanes. With the outside diameter of the vanes undersized to the baffle inside diameter by 0.020 inches, each vane is successively bonded to the cylinder at it's outside diamter with a low outgassing adhesive. The aluminum is electrolis deposited with a .0001" to .0002" nickel protectant then electro-deposited with .0003" copper plated using a geometry-specific anode. This is then put in a boiling Ebanol soultion at 214°F for an experimentally derived period of time (typically tens of minutes). A deionized water rinse, and air drying completes the process. At final camera assembly a single layer of silver teflon tape is applied to the outer surface of the outer vane.

To protect the lens against extreme cold, a 450-ohm Nichrome heater with a bimetallic switch turns the heater on when the unit drops below -6°C. The 1/2-inch wide heater strip is pressed against the outer diameter of the lens housing with an aluminum clamp, and the bimetallic switch is fastened to a flat on the clamp. The heater is powered by the spacecraft 30 ± 6 Vdc.

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, lens temperature, camera current levels, camera voltage levels and lens heater current. Additionally, switches were monitored to indicate ON/OFF status.

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. The lens thermistor was bonded to a flat on the lens heater clamp, and was left exposed as the protective "coffee can" prevented significant radiative heat transfer effects on its measurement.

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 [5], 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. A single Al 1100-0 CCD thermal strap is attached at the camera and directly to the camera heat pipe (part of the spacecraft Thermal Control System). To minimize particulate contamination to the lens and to minimize external, radiative thermal loads, NRL provided an enclosure for this camera (star tracker "coffee can"). The "coffee can" had a cover which was normally closed and could be opened when operation of the camera was required. 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 (for the CCD and electronic components), random vibration, thermal cycling, thermal vacuum and electronic burn-in. Table 2 summarizes the test environments.

CHARACTERIZATION AND CALIBRATION

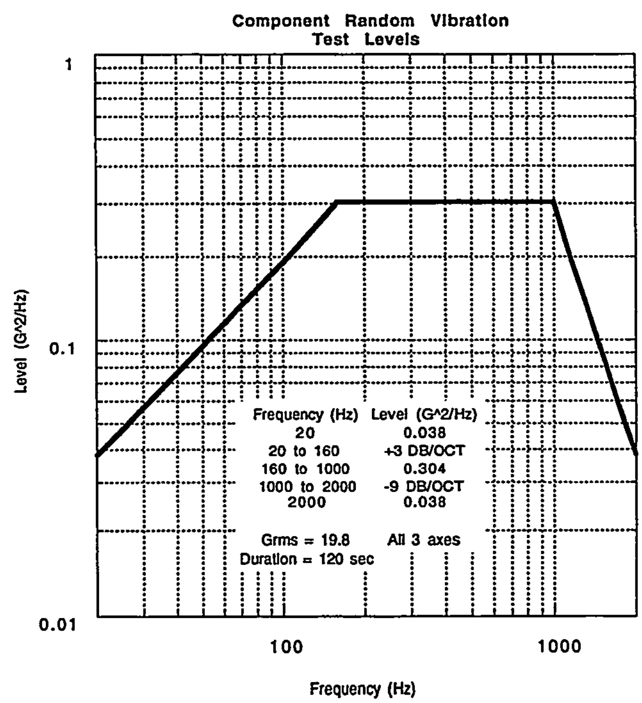
Extensive pre-flight calibration data were acquired using an automated calibration facility at LLNL. In a typical calibration configuration, a sensor was mounted inside an environmental chamber whose temperature was set to -20 to 20 °C which was the expected operating temperatures for the mission. Depending 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 computer; 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 measurements for the star tracker provided critical alignment data for integration to the spacecraft. These were location of the optical center of the lens relative to the CCD (x,y pixel coordinate), and optical boresight relative to the mounting feet of the camera (mechanical center). A two-dimensional angle map made in the laboratory, at roughly 0.5° increments, was made using a collimated source to determine the net $h = f(\theta_X, \theta_y)$ star centroid mapping function. This data set was fit to the nominal $h = \sin(\theta)$ mapping function of the lens to determine best fit for center pixel (θ_0) and focal length. A verification an d further refinement of this curve fit was made with the camera zenith-looking, then calculating a least-squares fit of the resulting quaternions taken over a several hour period.

Additional camera performance parameters measured included radiometric sensitivity; FPA uniformity; gain and offset scale factors; temporal / spatial noise; dark noise dependence on FPA temperatures, integration times or input voltage levels, spectral response of FPA; optical distortion map; point spread function and electronic warm-up time.

Due to the criticality of the star tracker to the flight control of the mission, exhasutive tests were performed on the lifetime of the optics, coatings, focal plane performance, and electronics performance under the mission required radiation dose.

Table 2. Clementine star tracker 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 • 19.8 g rms random vibration from 20-2000 Hz • 84 g peak acceleration for pyro-shock • > 50 Hz output frequency
Random Vibration	
Thermal Cycling	-30°C to 20°C, six cycles
Thermal Vacuum	by similarity with qualification unit, -20°C to 20°C
Electronic Burn-in	> 300 hours

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CLEMENTINE MISSION DATA

Mission data from the two star tracker cameras provided a myriad of raw star tracker images, useful for verifying the navigational capabilities of the camera, and a group of images to detect possible lunar horizon glow. The horizon glow data was gathered by pointing at the limb of the moon just before sunrise, detecting solar corona and possible scattering of dust particles (if present) close to the surface. The navigational requirements of the spacecraft were met using the star tracker/IMU combination as evidenced by the overalpping (correct pointing) of the mosaic UV/Visible and NIR lunar images. Fig. 8 is a single star tracker image of the moon with star matching triangles marked for reference. Fig. 8 shows data for the CCD and lens temperatures on star tracker A during orbit 72.

Figure 8. Earth's Moon viewed by star tracker B on March 5, 1994. To the right is Earth shine reflected off the Moon. To the left are three bright planets (Mercury, Mars and Saturn from left to right). The glow on the left occurs because the Sun is behind the Moon. Stars are visible to the eye also. The lower image shows the triangles generated by the stellar compass algorithm, demonstrating matching of a valid star pattern when the reflected light from the moon is blocked out. The algorithm ignored the three planets and the sun because they were not in correct positions to be stars.

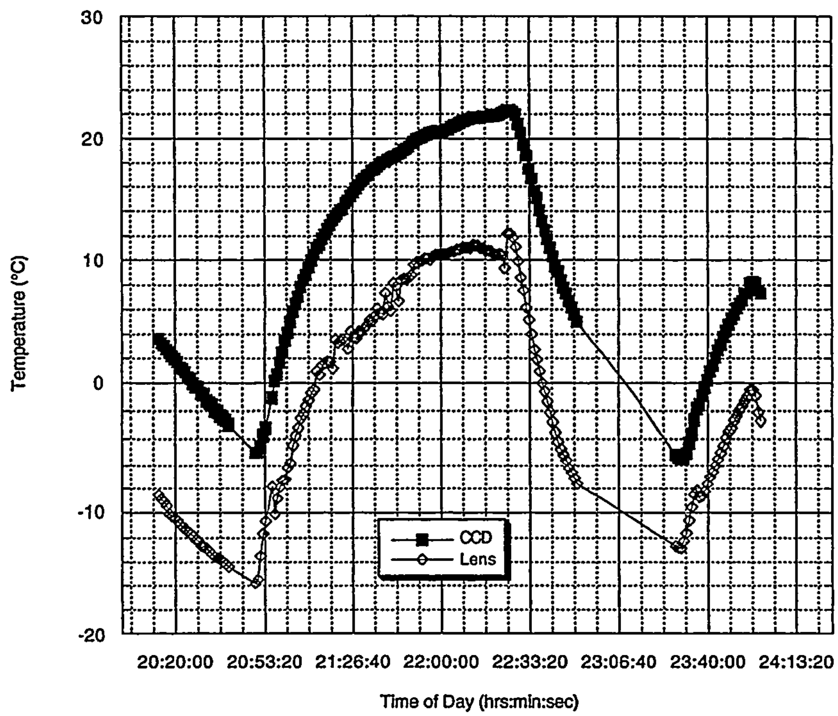

Figure 9. Star tracker A CCD and lens temperature for roughly one orbit on March 12, 1994. The CCD temperature exceeds the desired 10°C maximum value, but did not impair the star tracker stellar compass ability to achieve star matches.

LESSONS LEARNED

While the star tracker was very successful at meeting the mission objectives of this space flight, improvements could be implemented to reduce quaternion error and design complexity, without increasing the cost or mass of the star tracker camera. The most significant improvement of this version of the camera, applicable to extended space flights, would be the inclusion of an Multi-Phased Pin (MPP) focal plane array. The present CCD array will suffer increases in dark current with moderate levels (typical multi-year flights) of solar-flare radiation. In order to accommodate the solar flare potential for Clementine, the CCD temperature was specified to be controlled to less than 8°C through heat strapping to the spacecraft thermal control system (at a heat pipe). Cooling the CCD is a method effective in reducing dark current. At the maximum radiation requirement, the dark current variation, pixel-to-pixel, would have been large enough, even with the temperature limit, to degrade performance. MPP type arrays are much more radiation tolerant, and would not suffer in potential moderate radiation exposure.

Algorithm improvements can also be implemented to reduce quaternion error. These include a noise-reduction step and a signal processing improvement. Noise reduction would be accomplished by subtracting the nominal fixed pattern noise from the array, while software improvements would include distortion mapping and correction and "S"-curve error seen with the mass centroiding algorithm.

CONCLUSIONS

The star tracker stellar compass, as part of the suite of 6 light-weight, low power imagers [Refs 6 through 10] which were space-qualified for future Department of Defense flights, served as an integral part of the navigation system of the Clementine camera, providing accurate quaternion updates throughout the life of the Clementine mission. It is a space-qualified, proven, viable moderate-accuracy camera package, which, when coupled with the stellar compass software on the Clementine R3000 processor, provided quaternion data at 5 Hz rate. This system proved to produce valid quaternions for CCD temperatures up to 27°C, 17° above the limit specified prior to launch, demonstrating robustness beyond expectations.

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