Design and Fabrication of the *New Horizons* Long-Range Reconnaissance Imager

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ABSTRACT

The LOng-Range Reconnaissance Imager (LORRI) is an instrument that was designed, fabricated, and qualified for the *New Horizons* mission to the outermost planet Pluto, its giant satellite Charon, and the Kuiper Belt, which is the vast belt of icy bodies extending roughly from Neptune's orbit out to 50 astronomical units (AU). *New Horizons* is being prepared for launch in January 2006 as the inaugural mission in NASA's New Frontiers program. This paper provides an overview of the efforts to produce LORRI.

LORRI is a narrow angle (field of view=0.29°), high resolution (instantaneous field of view = 4.94 μrad), Ritchey-Chrétien telescope with a 20.8 cm diameter primary mirror, a focal length of 263 cm, and a three lens field-flattening assembly. A 1024 x 1024 pixel (optically active region), back-thinned, backside-illuminated charge-coupled device (CCD) detector (model CCD 47-20 from E2V Technologies) is located at the telescope focal plane and is operated in standard frame-transfer mode. LORRI does not have any color filters; it provides panchromatic imaging over a wide bandpass that extends approximately from 350 nm to 850 nm. A unique aspect of LORRI is the extreme thermal environment, as the instrument is situated inside a near room temperature spacecraft, while pointing primarily at cold space. This environment forced the use of a silicon carbide optical system, which is designed to maintain focus over the operating temperature range without a focus adjustment mechanism. Another challenging aspect of the design is that the spacecraft will be thruster stabilized (no reaction wheels), which places stringent limits on the available exposure time and the optical throughput needed to accomplish the high-resolution observations required.

LORRI was designed and fabricated by a combined effort of The Johns Hopkins University Applied Physics Laboratory (APL) and SSG Precision Optronics Incorporated (SSG).

Keywords: Pluto, KBO, space, *New Horizons*, imager

1. INTRODUCTION

The *New Horizons* instrument payload includes the LORRI instrument, the focus of this manuscript; Alice, a UV spectrometer; Ralph, a visible/IR imaging spectrometer; the Pluto Energetic Particle Spectrometer Science Instrument (PEPSSI); the Solar Wind Around Pluto (SWAP) instrument; a Student Dust Counter (SDC); and the Radio Science Experiment (REX). The optical instruments (Ralph, Alice, and LORRI) are all aligned to view a common boresight direction, and the spacecraft will rotate as required to provide pointing during the Pluto and Charon encounter.

LORRI is designed for high resolution and responsivity in the visible wavelengths. LORRI is to perform its measurements while *New Horizons* approaches Pluto and its satellite Charon in July, 2015, obtaining images from a range as close as 11100 kilometers to Pluto at a fly-by speed of 13.77 kilometers per second. These conditions apply for the opening of the baseline mission launch window; the arrival date moves to later years (as late as 2020) and the flyby speed is reduced (as low as 8.06 km/s) toward the end of the baseline mission launch window and for the back-up

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mission. If *New Horizons* launches within the first 23 days of the baseline mission launch window, there will also be a Jupiter system flyby, where LORRI will image the atmosphere of Jupiter, its ring system, and several of its satellites. Finally, after the Pluto and Charon encounter, the *New Horizons* spacecraft will be targeted to encounter a Kuiper Belt object, at which LORRI will again obtain high resolution images.

The main objectives of LORRI are: (1) obtaining high resolution images of Pluto and Charon during the approach phase, including the hemisphere that will not be observed during closest approach, (2) taking images at closest approach with instantaneous field of view (IFOV) of approximately 50 meters per detector element and (3) obtaining navigation images required to make course corrections. LORRI's reflective telescope is a Ritchey-Chrétien, with a field-flattening lens group near the focal plane. The digital image is captured by a high-efficiency, back-illuminated E2V Technologies 47-20 CCD. The field of view (FOV) is 0.29˚ x 0.29˚; the 1024 x 1024 square detector elements have an IFOV of 5 μrad. A summary of the characteristics of the LORRI instrument appears in Table 1.

The LORRI instrument is mounted inside the *New Horizons* spacecraft, which is designed to be near room temperature. As the telescope views cold space, and the CCD is designed to operate at ≤–70° C, the thermal implementation of the system was a challenge. In order to maintain optical performance, a material with high thermal conductivity and low coefficient of thermal expansion (CTE) was required. As a result, the LORRI optical telescope assembly (OTA) has mirrors and a metering structure fabricated from silicon impregnated silicon carbide (SiC).

Table 1
Summary of LORRI Characteristics

Telescope aperture	208 mm
Telescope focal length	2630 mm
Field-of-view	0.29° x 0.29°
Pixel field-of-view	4.94 μrad (0.00028°)
Wavelength range	350-850 nm
Detector type	E2V Technologies 47-20 CCD
Pixels per image	1024 x 1024
Typical exposure times	0.05-0.20 sec

2. SCIENCE OBJECTIVES AND REQUIREMENTS

The *New Horizons* mission will perform the first reconnaissance of the Pluto-Charon system and the Kuiper Belt. Pluto is an ice dwarf planet with a significant atmosphere consisting mainly of nitrogen. High resolution images from LORRI will yield important information on Pluto's geology and surface morphology, collisional history, and atmosphere-surface interactions. Will Pluto have a young surface, with evidence of endogenic activity like cryovolcanism? Will there be evidence for tectonism and rafting of ice floes like on the fractured surfaces of Europa or Triton? Will there be evidence for surface winds forming dunes (dunes on Pluto will be mostly grains of nitrogen ice)? Pluto is known to have an active surface, with changes in surface colors and reflectances observed by Earth-based telescopic monitoring. LORRI's high resolution images will reveal features as small as 100 m on Pluto (260 m on Charon).

Charon is Pluto's giant satellite: at about half the size of Pluto it is larger than any other planetary satellite relative to its primary. Unlike Pluto, Charon has no sensible atmosphere, and it probably has an old surface that may preserve features like craters dating to back to the formation of the outer solar system. LORRI data will play a critical role in determining the crater size distribution and morphologies on Charon. Equally important, LORRI images will provide precise measurements of the shapes and sizes of both bodies. After the Pluto-Charon encounter, *New Horizons* will make the first visit to one or more Kuiper Belt objects. Owing to the likely small size of these targets, LORRI's high resolution is especially important to capture as much surface detail as possible. Will these Kuiper Belt objects look like the asteroid Eros, or will there be bizarre surface features like the flat-floored, steep-walled depressions (craters?) found on the nucleus of comet 81P/Wild 2?

2.1 Key science issues

The *New Horizons* mission has a long focal length, narrow angle imager for several reasons. Pluto is the smallest planet, and *New Horizons* flies by quickly, so the encounter science observations occur within one Earth day – but with LORRI, *New Horizons* will be able to image the Pluto system at higher resolution than any Earth-based telescope can (even the Hubble Space Telescope, or its successor in 2015) for 90 days prior to encounter. These images will provide an extended time base of observations, for studies of the shapes, rotations, and mutual orbits of both Pluto and Charon, and for characterizing surface changes.

Moreover, Pluto and Charon both rotate at the same rate as for their 6.4 day mutual orbit, always keeping the same faces towards each other. Hence, during the near encounter, which lasts less than an Earth day, only one hemisphere of each body, that which faces *New Horizons*, can be studied at the highest resolution. The opposite faces of both Pluto and Charon are last seen some 3 days earlier, when the spacecraft is still ~4 millions of km away. Despite this distance, LORRI will obtain images with 40 km resolution. These will be the best images of the portions of Pluto and Charon which are not seen during the near encounter period.

Finally, we have not yet discovered the Kuiper Belt object(s) to which *New Horizons* will be targeted after the Pluto-Charon encounter. Extensive Earth-based observing campaigns are planned to do so. However, even after discovery, the heliocentric orbits of the targets cannot be measured with sufficient accuracy from Earth to enable the *New Horizons* spacecraft to fly to them, unless the targets are also observed directly from the spacecraft. The direction in which the target is seen from the spacecraft is then used to steer the spacecraft to the target, by optical navigation. LORRI is expected to play a key role, by making the first and highest resolution detections of the Kuiper Belt target object from *New Horizons*.

2.2 Measurement requirements

LORRI is required to obtain high resolution, monochrome images under low light conditions. Other instruments on *New Horizons* have multispectral and hyperspectral capabilities. At Pluto encounter, 33 AU from the Sun, the illumination level is ~1/1000 that at Earth, but Pluto is an unusually bright object with a visible albedo of ~0.55. At the Kuiper Belt object, likely to be encountered outside 40 AU from the Sun, the illumination will be still lower, and the object will be darker, with an albedo of typically ~0.1.

During the approach to Pluto, which occurs under high sun conditions (small phase angle or Sun-Pluto-spacecraft angle), LORRI is required to image the surface of Pluto at signal-to-noise ratio (SNR) > 100 in single frames. The encounter geometry is such that near closest approach to Pluto, where the highest resolution images would be obtained, LORRI views regions near the terminator under low sun conditions and still less illumination; here LORRI has the goal of imaging at SNR > 20 in single frames. Likewise, at the Kuiper Belt object LORRI has an SNR goal > 20.

The resolution requirement near Pluto closest approach is for LORRI to resolve 100 meters per line pair at a distance of 10,000 km from the surface. Given the IFOV = 4.94 μrad (Table 1), the derived requirements on imaging quality are that the system modulation transfer function (MTF) exceed 0.05 at 38.5 cycle/mm, with an ensquared energy exceeding 0.3 in the highest pixel. LORRI is designed to meet these requirements not only at nominal operating temperature (as low as ~-100°C for the telescope), but also at room temperature.

For optical navigation, LORRI is required to be able to image a star of visual magnitude V=11.5 at SNR>7 in a single 100 ms exposure, with 30% of the light in the highest pixel. LORRI has a 4x4 pixel binning mode, for which its limiting magnitude requirement is V>17.4 in a single exposure of 9.9 s. This 4x4 pixel-binning mode will be used to search for the Kuiper Belt target object. At 40 AU from the Sun, LORRI is predicted to be able to detect a 50 km diameter object, of albedo 0.04 and at phase angle 25°, from a distance of 0.35 AU, more than 40 days before the object would be encountered. This is ample time for targeting of the spacecraft.

3. DESIGN OVERVIEW

The LORRI instrument is composed of four subassemblies, with electrical harnessing connecting them. The four are located in close proximity to each other. Included are the OTA, the aperture cover door, the associated support electronics (ASE), and the focal plane unit (FPU). Except for the door, all are located on the central deck of the spacecraft; the door is mounted to a spacecraft skin panel. With the exception of door control, several spacecraft thermistors and two decontamination heaters, all electrical interfaces between LORRI and the spacecraft are through the ASE.

3.1 OTA assembly

The OTA assembly is tube-like in appearance (figure 2b). With the exception of the CCD and blanketing, the OTA was designed and built by SSG Precision Optronics, Inc., of Wilmington, Massachusetts, USA. The imager optics are primarily constructed of SiC, including the reflecting optical elements. The telescope is a 2630 mm focal length, f/12.6 Ritchey—Chretien. The OTA has a back illuminated (high quantum efficiency) CCD at its focal plane. A set of three field-flattening fused silica lenses, located just in front of the CCD, are the only refractive elements in the system.

The SiC metering structure holds the mirrors and field flattener. It is a monolithic structure consisting of a primary mirror (M1) bulkhead, short cylindrical section, and three-blade spider with secondary mirror (M2) mounting. The field flattener assembly mounts to the M1 mounting plate, and protrudes through the M1 mirror.

The metering structure is mounted to the graphite composite baffle using 3 titanium vibration-isolating feet. The baffle assembly is mounted to the spacecraft using six glass-epoxy legs, which provide thermal isolation. The entire OTA is covered with multi-layer insulation (vented away from the OTA), except for the interface to the door.

3.2 Door assembly

A door protects the LORRI instrument from contamination during ground processing and launch. It also keeps light from entering the telescope during the early part of the mission. The door is spring loaded, with single shot operation. It is released by one of two redundant paraffin actuators. It is fabricated primarily from aluminum. It is directly mounted to the spacecraft and sealed to the baffle using Kapton blanketing to allow slight movement between the two. Mounting to the spacecraft employs six flexures, providing thermal isolation. The multi-layer insulation is designed to deflect spacecraft venting so that particles do not enter the LORRI telescope during launch ascent.

3.3 ASE assembly

The ASE consists of three 10 cm by 10 cm printed circuit cards electrically interfaced to one another via stackable connector. They are in a housing of magnesium, which is mounted directly to the spacecraft deck a short distance from the telescope assembly.

3.4 FPU assembly

The FPU consists of a magnesium box and a flex circuit connecting to a small electronics board mounted at the telescope's focal plane. The box houses a 15 cm by 10 cm circuit card which serves to control the CCD, and interface it to the imager board of the ASE. This box is mounted to the spacecraft deck, and operates near room temperatures. The smaller board holds the CCD itself, and is mounted on thermal stand-offs at the telescope focal plane. The CCD and small board operate at ≤-70° C.

4. OPTICAL DESIGN

4.1 Design trades

The primary driver for the design of the LORRI instrument was meeting resolution requirements as described in section 2.2. The resolution is limited by a number of factors, including the stability of the spacecraft while an image is being exposed. The stability of the spacecraft is expected to be ≤ 34 μrad per second. The minimum exposure time is limited by the frame transfer time of the CCD. In order to successfully remove image smear which occurs during transfer, the exposure time must be at least three times the frame transfer time. At the time of the optical design, frame transfer time was expected to be approximately 15 milliseconds, and a minimum exposure time of 50 milliseconds was assumed.

Given the spacecraft stability, it is desirable to minimize exposure time. However, margin must be maintained in the event that exposure time must be adjusted. For this reason, it was determined that the system would be designed for an exposure time range between 50 and 200 milliseconds, with 100 milliseconds design nominal. Over this exposure range, spacecraft stability would be ~2 to ~7 μrad.

After the range of exposure times was determined, IFOV had to be traded. A smaller IFOV yielded higher resolution, although little would be gained dropping far below the expected spacecraft stability. A larger IFOV gave a large FOV, and minimized the required aperture. In parallel, aperture size was traded. Diffraction started to become a significant factor in system resolution when the entrance pupil became appreciably smaller than 200 mm diameter. Strict mass limitations combined with cost limitations prevented increasing the aperture to significantly larger than 200 mm diameter. The trade eventually settled at 208 mm.

As reasonable assumptions could be made about the type of telescope and detector, and their associated efficiencies; this information could be combined with the target sterance and nominal exposure time to bound the IFOV. The result was an IFOV of approximately 5-μRadians, which in turn gave an effective focal length of 2630 mm. The FOV of the final design was 0.29° square.

The requirement for a fairly large aperture drove the telescope to be a reflecting type. Mass and cost limitations, combined with the field size drove the design to be a Ritchey-Chrétien design. Refractive elements were used as field flattening lenses, as the Ritchey-Chrétien focal plane curvature over the flat CCD would have limited imaging performance without them. As there was no requirement for color imaging there was no need for a filter wheel—allowing for mass and cost to be minimized.

An optical raytrace layout for LORRI is shown in Figure 1, and Table 2 provides the optical design parameters.

Figure 1
Optical Ray Trace Layout

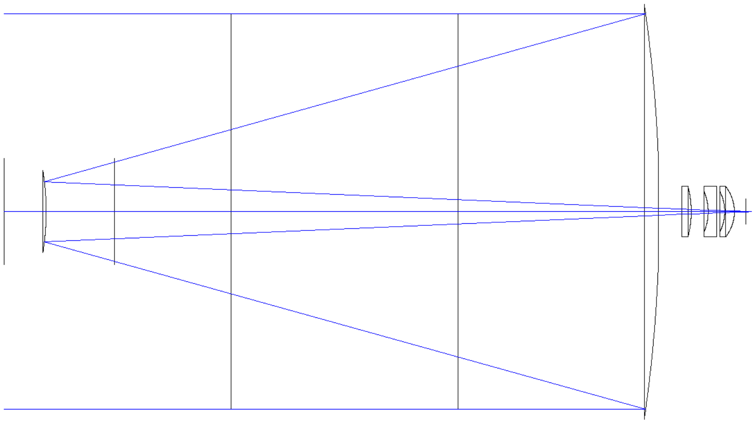


Table 2
Summary of LORRI Optical Design Parameters

Component	Radius [mm]	Conic Constant	Material	Spacing [mm]
System Aperture Stop (208 mm diameter)	N/A	N/A	N/A	105.537
M1 (concave)	757.786	-1.0120	Vacuum Reflection	321.564
M2 (convex)	135.966	-2.0194	Vacuum Reflection	333.222
L1, S1	∞	-	Fused Silica	5.080
L1, S2 (convex)	52.172	-	Vacuum	8.890
L2, S1 (concave)	27.305	-	Fused Silica	4.572
L2, S2	∞	-	Vacuum	4.090
L3, S1 (concave)	23.571	-	Fused Silica	5.050
L3, S2 (convex)	21.590	-	Vacuum	8.890
Detector Array	∞	-	Silicon	N/A

4.2 Stray light control

The complete opto-mechanical sensor of LORRI was evaluated with the computer aided design model including all optics into a straylight analysis package. The surface treatments include the specular reflections and bidirectional reflectance distribution function of the Z-306 paint, primary and secondary mirrors, field group optics and focal plane.

The system's first order analysis baffled direct paths to the focal plane assembly (FPA). This required balancing the telescope magnification and obscuration which directly affect the optical sensitivities and MTF respectfully. The primary and secondary baffle tubes are sized to minimized the obscuration and suppress direct paths to the FPA's active area. Out of field stray light verification was determined by generating point source transmittance curves with an angular cross and along scans (- 70 to +70 degrees) in determining any obscured paths with unacceptable amplitude.

The OTA stray light analysis required multiple baffles, fabricated from graphite composite, surrounding the metering structure. In addition, there is an inner baffle extending out from the hole in the M1 mirror. This inner baffle has both vanes and threading in its interior. The results show that out of field stray light is adequately suppressed and ghosting is acceptable.

4.3 Contamination control

The internal cleanliness requirements for the LORRI OTA per the LORRI performance specification are a beginning of life = 250 A/ 2 and an end of life = 300 A per MIL STD 1246B.

4.3.1 Derived throughput requirements

The instrument contamination control requirements were derived from performance requirements of the instrument and take into account the number of contamination monolayers light must pass through to arrive at the CCD; for LORRI the number of monolayers is eleven.

LORRI specification requires beginning of life cleanliness to level 250A/ 2 and end of life level 300A, thus allowing an increase of A/ 2 or about 50Å per surface. Tribble[1] Figure 2-6 gives an average absorption coefficient, over this wavelength range, of 0.5E6/m over the wavelength range 350 nm to 850 nm, so for a film thickness of 5E-9m total throughput will be 0.973.

Less than 0.1% total surface area coverage (level 320, see Tribble Figure 3-9) is allowable on the CCD. Total theoretical reduction in efficiency is: 2.75% molecular + 1.1% particulate = 3.85%, round to 4%.

4.3.2 Thermal performance requirements

The baseline mission requires decontamination of the CCD before door opening with CCD temperatures ranging from >-18°C. This will require the use of decontamination heaters. Decontamination can be achieved at lower temperatures, however long time periods may be necessary to desorb water.

4.3.3 Integration and test

All components internal to the LORRI OTA were vacuum baked to an outgassing rate no greater than 1E-13 g/cm^2s with hardware at 40°C and quartz crystal monitor at -55°C. All other components adjacent to the OTA were vacuum baked to a rate no greater than an order of magnitude higher. A few flight items were vacuum baked in a non-instrumented "bell jar" type of chamber using a criteria that rate of base pressure change could be no more than 1E-7 torr/hour when averaged over five-hours. Final outgassing rate of the LORRI telescope assembly was verified in the APL 3D3 vacuum chamber. Scavenger plate analysis showed the following chemical species: 1) alkyl acrylates (64.9 %), adhesive monomer; 2) 2-dimethoxy-2-phenylacetophenone (35.1%), photoinitiator; 3) caprolactam (trace), and ring opening monomer.

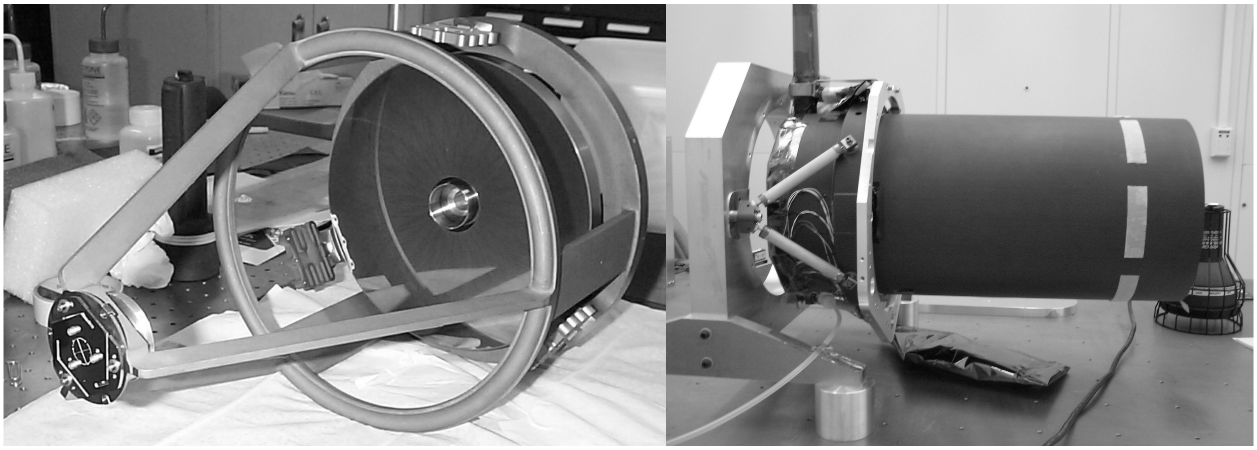
During vibration testing in the vertical (aperture pointed up) configuration many small particles landed on the CCD. About half of these particles were removed with an ionized nitrogen blow-off conducted during replacement of a field programmable gate array.

The LORRI telescope assembly has remained under a nitrogen purge during all phases of integration and test, except for those limited times when images are being taken or when under vacuum, and will remain under purge until launch.

5. MECHANICAL IMPLEMENTATION

Figures 2a and 2b show the mechanical implementation of the LORRI instrument.

Figure 2a and 2b LORRI Photographs



5.1 Telescope

The stringent optical, thermal and structural requirements for the LORRI OTA presented many design challenges. The requirements of significance to the OTA design are discussed in detail below, and the design and configuration is addressed in the context of these requirements.

5.1.1 Optical requirements

The LORRI OTA is an MTF driven Ritchey-Chrétien design, with system throughput being of distinct importance due to limits on available exposure time. The derived top level system root-mean-squared (RMS) wavefront error requirement based on the MTF requirement was < 0.10 waves @ 632.8 nm, valid over an operating temperature range of -125C to 40C and after g-release. The system throughput requirement drove a surface roughness requirement on all optics to a goal of < 20 Å RMS, as well as the implementation of a comprehensive baffling strategy which includes a main baffle tube, an M1 baffle with inner and outer baffle veins, an M2 baffle, and a serrated lens cell spacer to reduce stray light. All baffle design features were optimized through TracePro analysis.

Surface roughness requirements for the optics was achieved by depositing a 10 micron layer of silicon on the M1 and M2 after initial polishing, and post-polishing the final figure to produce a thickness of 3-5 micron. The small final thickness of the silicon layer minimizes bimaterial effects under soak. Furthermore, all optically exposed surfaces were painted with Aeroglaze Z306 black paint to reduce stray light effects.

An Invar 36 lens cell assembly mounted to the OTA bulkhead, and projecting up through the central hub/hole in the M1, houses the fused silica lenses that allowed for field flattening to achieve the requirement of <0.1% distortion at all points over the full field of view. In addition, all refractive elements are flats and negative spheres to reduce back reflections on the focal plane.

5.1.2 Thermal requirements

Not least of the design challenges was the extreme thermal environment, where the LORRI instrument is to be mounted to, and surrounded by, a +40ºC temperature spacecraft while pointing primarily at cold space. The main challenge under this scenario is to minimize defocus due to gradients developed in the OTA metering structure. The derived requirement is to limit the heat loss from the spacecraft to the OTA to less than 12 W, requiring conductive isolation at the interface and near zero radiative coupling to spacecraft. The gradients in the OTA metering structure are to be limited to 2.5 C axial and 1.0 C lateral, with only 0.5 W heater power available for mirror gradient control.

Given the thermal boundary conditions, and without means for in-flight focus adjustment, the challenge was to choose a suitable material and design configuration such that gradients and their resultant effects will be minimized.

The desired configuration is an athermal, single material solution, which is self-compensating under soak conditions. SSG's SiC 55A was chosen due to its inherent high conductivity, which acts to minimize gradients, and its low CTE, which minimizes the thermal strain impact of such gradients, in effect providing an ideal material solution for this application. Invar 36 being a good match to SiC 55A over the temperature range of interest was chosen for the metallic inserts that would allow bolting together of the OTA assembly. All invar inserts, as well as the M2 foot, were bonded to the SiC using Epibond 1210A/9615-10 epoxy, due to its favorable strength properties at cryogenic temperatures and its extensive flight legacy. In addition, the OTA is mounted inside of the telescope baffle tube, which is highly conductive K13C graphite composite. The baffle tube is an essential feature of the thermal design as it provides a relatively uniform cold sink along the length of the telescope which helps to reduce longitudinal thermal gradients.

Additional thermal control features on the LORRI telescope help to reduce system gradients. Mounting the telescope to the spacecraft via G-10 isolators acts to sufficiently isolate the OTA conductively from the spacecraft deck. Furthermore, the isolators are gold coated and filled with Kapton, which helps to minimize radiative coupling to the surrounding spacecraft. Covering the appropriate OTA and spacecraft surfaces with MLI (Multi-Layer Insulation), minimizes radiation coupling between the OTA and the spacecraft deck. Gold coating the M2 mount plate (space-pointing side), reduces the radiative coupling of M2 from space, and decreases M1-M2 gradients. The LORRI MLI, which represents 15% of the instrument mass, consists of 23 separate pieces.

Areas where material mismatches occur are flexured or otherwise configured to minimize induced strain, and resulting optical degradation under soak. The M2 is mounted to an Invar 36 mount plate, which in turn mounts to the end of the spidered region of the SiC 55A OTA structure. To minimize the potential for despace or decenter of the M2 under thermal soak, the mount plate is flexurized radially. The M2 and M1 magnesium baffles are flexure mounted to the OTA structure (SiC) and the lens cell (Invar 36) respectively. The system aperture stop is made of Al 6061-T6 and is mounted to the middle ring of the OTA (SiC) structure and is also flexured radially to minimize induced strain. The CCD mount plate is Al 6061-T6 and mounts to the OTA structure via titanium flexures which have the dual purpose of mitigating thermal strain, and thermally isolating the CCD from the structure. The G-10 mounts have titanium post flexures on either end to allow for mitigation of thermal strain between the spacecraft deck, and the OTA itself, as well as taking up any strain that is induced during mounting. Additionally, the OTA itself is mounted to the K13C baffle tube via titanium isolators, which act to mitigate thermal strain and conductively isolate, as well as isolate the telescope structure from vibrations.

An additional, and pivotal thermal requirement is that the CCD must be maintained at a temperature of < -70C, while mounted to the OTA structure. This requirement is met by mounting the CCD to a bracket which is mounted to the OTA via conductively isolating flexures (titanium flexures); the CCD bracket is in turn attached to a gold-coated beryllium S200F conduction bar which is bolted to a gold-coated beryllium S200F radiator which mounts outside of the spacecraft and radiates to space (space-looking side of radiator is painted white with Aeroglaze A276). Since the radiator is mounted to a separate spacecraft panel from the OTA itself, there must be some compliance to allow motion between the two. To this end, a highly conductive 1100 series aluminum alloy S-link is employed to connect the aluminum CCD mount bracket to the conduction bar. In order to avoid any charge build-up on the radiator from reaching the focal plane, there is a thermally conductive, electrically isolating layer of Thermabond silicone material bonded between the interface of the S-link and conduction bar. The adhesive bond between the flexible link connecting cold finger to CCD required an adhesive with high thermal conductivity and good low temperature flexibility; this adhesive is the subject of a previous paper[2].

The LORRI in-flight temperatures were predicted via the creation of a finite difference thermal model which included all conductive and radiative heat transfer. A thermal balance test of the instrument was performed which validated the thermal model in five separate test cases. The results of thermal balance testing indicated that the 0.5 Watt gradient control heater will not be required in flight.

5.1.3 Mechanical/structural requirements

The structural requirements of the OTA were geared towards achieving the lightest possible design, while maintaining performance over operational temperatures and allowing for the stiffest design that will survive the intended launch environment. The requirements as such are a maximum mass of 5.64 kg, a minimum resonant frequency of 60 Hz, and survival under a demanding random vibration and sine vibration environment, with response limiting allowed to 12dB above input, as well as a quasi-static 25 g's requirement.

The inherently high stiffness to weight ratio of SiC, (~4.5X that of aluminum) allowed the fabrication of an aggressively light-weighted structure, with a highly light weighted M1, (77% light weighted, open back, hub-mounted design), to minimize weight. The main baffle tube was fabricated from graphite composite, (K13C2U, M55J, and T300), another very high stiffness to weight material, (~2.5X-4X that of aluminum), and the internal smaller baffles were fabricated from a light weight magnesium alloy (ZK60A).

To survive the aggressive launch environment it was necessary to incorporate vibration isolation, thereby reducing the frequencies of the largest modal mass contributors (those of the metering structure and optics), to ensure that they see the smallest resultant accelerations possible. Titanium isolators were incorporated to mount the structure to the main baffle tube at three points approximately at its center of gravity location. Mounting the structure in this way acts to effectively decouple the translational and rotation modes of the isolated structure, to further reduce the responses under vibration.

Another important structural design consideration was to minimize any potential for mount-induced distortion at the optics, or on the OTA as a whole. Intimately connected to this design consideration is the requirement for the OTA to mount to a surface with only moderate mounting coplanarity, without degradation of optical quality. This requirement stems from the inability to accurately control the coplanarity of the mounting features on the highly light weighted aluminum honeycomb panels that make up the spacecraft deck. To overcome this challenge, a 3-point mount was adopted, with the bases of each of the three mount locations on the OTA outfitted with a ball joint, that can be loosened to allow for rotation, and then re-tightened once in a strain-free configuration if required.

At the interface between the main baffle tube and the OTA inner assembly, the vibration isolators also act to mitigate any mount-induced strains due to their inherent compliance. The flexurized mount plate at the M2 serves the dual purpose of controlling thermally induced distortions, as well as mount-induced distortions; the CCD mount flexures also serve this dual purpose.

Due to its mass, it was not possible to flexurize the primary mirror, as the low resultant frequency and dynamic responses would have increased the risk to the OTA under vibration. Instead the M1 is "hub-mounted"; that is the M1 has a post and a “foot” with three invar inserts that bolt to an “M1 mount plate”. The M1 mount plate is in turn bolted to the structure. Because the lens cell is made of Invar and mounts to the structure, in close proximity to the M1, the mount plate helps to separate any induced thermal strain in the structure from being transferred to the M1. As for strain between the M1 and M1 mount plate, this is minimized by lapping the mating surfaces to optical flatness.

5.2 Focal plane detector mounting

The E2V Technologies CCD is mounted in a ceramic dual inline package (DIP). The CCD is bonded with Epibond 1210 epoxy to a small molybdenum heatsink, which in turn is attached to an aluminum heatsink with a single screw and Uralane. A small printed circuit card is behind the heatsink and soldered to the CCD leads. This printed circuit card, in turn, is connected by a thin, flexible circuit to the main FPU electronics box. The FPU box is mounted directly to the spacecraft, beneath the OTA.

The CCD array does not have a window, in order to avoid scatter and multiple reflections. The array was protected using a removable ground support equipment window prior to installation on the instrument. The readout area of the CCD was protected from unintended light by an aluminum reflective layer coated onto the silicon. In order to be sure that a bright light source would not be able to produce an image through the aluminum layer, a black anodized aluminum plate was installed over it.

5.3 Door mechanism

LORRI is protected from contamination and solar illumination using a release-only door mechanism. The door is mounted to the exterior of the spacecraft, and the LORRI baffle tube extends into it to form a contamination seal. The door is aluminum, with blankets to provide thermal control prior to deployment. The mechanism uses redundant springs and redundant paraffin actuators for deployment. A port allowing for installation of a witness mirror or small window is also part of the door.

5.4 Focus and alignment

When the OTA was assembled at SSG, a convex spherical reflector was placed centered at the focus using interferometry. Metrology, combined with knowledge of the shim size used to connect the reflector to the carrier plate, allowed SSG to report the location of the focus referenced to the interface location on the carrier plate. SSG also provided a reference mirror on the back of the secondary mirror mount. This mirror was used to align the telescope such that its line-of-sight was in a direction parallel to the reference mirror’s normal. Two optical reference flats at right angles to the line-of-sight were also mounted to the LORRI metering structure for use in alignment monitoring after mounting to the spacecraft.

The depth of focus for the LORRI system at the detector is tolerant enough that mechanical tolerances on the CCD were used in combination with the SSG provided focus location, allowing for initial shim sizes to be selected for the system focusing. After the CCD was installed, the focus was checked.

A 300 mm aperture, f:5 off-axis parabolic collimator was then used to project a point-like image into LORRI. The collimated point-like image was produced by placing a laser unequal path interferometer (LUPI) at the collimator focus, and using a flat to focus and align the LUPI to the collimator. The flat was then removed, and the LUPI used to provide a point source image. As the LORRI image size at best focus was close to the predicted, we know that the projected image was small enough to not affect the measurement. A series of exposures were made at nine points in the LORRI field by moving within the field using fold mirror tips and tilts. At each location, the spot was centered on a detector element by viewing the live image, and balancing the wings of the image symmetrically about the center detector element. This was repeated for seven focus adjustments of the collimator, with slight measured changes from nominal to allow for deterministic shimming of LORRI. Data from these exposures were examined to find the best LORRI focus versus the collimator adjustment. New shims were installed were then installed to move the plane of the CCD onto the plane of best focus.

Once at nominal focus, the CCD was centered on the optical axis by use of a theodolite aperture sharing between the reference mirror on the back of the secondary mount and the primary mirror. The theodolite was autocollimated on the reference mirror, and the azimuth and elevation recorded. The theodolite was then used to view the four corners of the CCD off the primary mirror, and these azimuth and elevation values recorded and averaged. The CCD location was then shifted in the plane of best focus such that the average of the four CCD corners was within tolerance of the normal to the reference mirror.

After the best focus was found in ambient conditions, LORRI was installed in Goddard Space Flight Center's Diffraction Grating Evaluation Facility for a focus check at flight-like thermal and vacuum conditions. This was done by viewing the collimator beam, which projected a small pinhole image into LORRI, and stepping the spot over the field by tilting LORRI. It was found that LORRI had ensquared energy of ~30%, limited primarily by CCD performance.

Prior to delivery to the spacecraft, LORRI's line-of-sight was measured relative to the optical reference flat mounted to the back of the secondary mirror support. Additionally, the roll was measured by viewing the CCD corners, and referencing to the orthogonal alignment mirrors. These data, combined with measurements done referencing the flats to the spacecraft coordinate system, showed that LORRI's line-of-sight was within mission requirements. Tracking of the LORRI's alignment references through the spacecraft environmental test program has not yet shown any significant movement versus the spacecraft coordinate system.

6. ELECTRONICS IMPLEMENTATION

The electronics for the LORRI instrument primarily consist of the ASE and FPU. The ASE contains three printed circuit cards. These are the low voltage power supply (LVPS), the event processor unit (EPU), and the imager input/output (IM I/O). The ASE is the primary interface between the spacecraft and the FPU board, which controls the CCD.

6.1 FPU and CCD

The CCD electronics board, called FPU, is required to read out a complete image in 1 second, corresponding to a pixel rate of about 1.3 MHz. Each pixel is represented by a 12 bit binary word in these FPU designs. The pixel rate is higher than the number of active pixels times the frame rate to clock out "dummy" pixels and lines and to synchronize with clocks used by the rest of the spacecraft electronics. The data from the FPU is a bit serial stream at a 16 MHz clock rate. It is important that the CCD be highly sensitive, have a wide spectral coverage including the near ultraviolet, and still have antiblooming so that bright sources in the field of view will not lead to loss of fainter objects. The imager looks at distant objects so that the scene is quite static and in consequence rapid frame transfer is not an issue. In order to enhance the sensitivity to dim diffuse objects, on chip binning of 4 by 4 pixels is included in the design. These requirements lead to the choice of the E2V Technologies CCD47-20. This is a 1024 by 1024 pixel frame transfer CCD with 13 micron square pixels which is back illuminated for high quantum efficiency and incorporates antiblooming protection. The transfer time for this device is 13 milliseconds. The noise requirements for the FPU are also fairly modest at 40 electrons, well above the CCD read noise which is calculated to be about 10 e at the readout time of about 0.7 microsecond per pixel. The LORRI camera is able to take pictures with exposures greater than one second. This is fitted to the general 1 Hz frame rate by dropping frames during a long exposure. The E2V CCD uses three phase clocks for image zone, memory zone and line transfer. In general, exposures of 0.05 to 0.20 seconds for LORRI are typical.

6.1.1 Driving the CCDs

All CCDs have a number of clocks which must be driven to specific levels for satisfactory operation. These clocks are highly capacitive, particularly for the image and memory areas of the chip, and also have capacitive coupling between different phases. The capacitance to be driven is as high as 15 nF, with clock voltage swings as large as 10 volts, and with transitions in less than 500 ns. This implies a peak current requirement of <1.5 amps per phase. The phases are staggered and these peak currents are not simultaneous except for the image and memory zone clocks while an image is being transferred. The simplest way to drive these clocks would be with an amplifier with a low output impedance, controlling the pulse shape at the input. In practice suitable fast operational amplifiers with this level of output are not available. Instead we use Micrel MIC4427 drivers which are intended to drive the gates of power MOSFETs. They are designed to drive high capacitance loads at the required voltage levels from logic level inputs and are therefore well suited in terms of robustness, and they are flight qualified, having been used on the NEAR imager FPU. These parts are compact, with two drivers per 8 pin DIP, and are power efficient since they switch between supplies. They are a switching, not a linear device, so that low and high voltage levels are obtained by suitable choice of supply voltages, and transition rates must be adjusted at the output. This is done by adding series resistance which adds to the internal switch resistance of the drivers, forming a simple time constant with the capacitance of the CCD phase. This is very effective except when another phase changes state. This edge couples through to the other phases by way of the interphase capacitance, producing positive and negative pulses on a resting gate. These coupled edges are of small amplitude and do not affect CCD clocking. Different clocks require different voltage levels in this device, but they can be accommodated conveniently by resistive dividers at the output, resistors already being present to control clock transition times. The result is that only a few voltage levels are needed for the clock driver linear regulators. This CCD requires 29 volts bias for the output field effect transistor (FET) which was not available from the local converter. A charge pump with pre and post regulation was used to generate this voltage, the regulation being required because the output amplifier is driven from this line and the CCD output is sensitive to variations in the level.

The output of the CCD is at a relatively low impedance of a few hundred ohms and consists of serial samples of zero and signal levels from each pixel. The timing is controlled by signals sent to the serial output register and reset gate on the CCD. The output signals are of less than one volt amplitude negative going on a steady potential of nearly 20 volts. The standard method of extracting the signal is called correlated double sampling. In this technique the zero level from a pixel is subtracted from the following pixel value by an analog circuit. This technique removes noise in resetting to the zero level after each pixel value, and also removes the large steady potential on the CCD output. This is done before digitization so that the dynamic range of the analog to digital converter can be used on the signal. The zero level is sampled on a capacitor and this stored value is subtracted from the signal. This capacitor can conveniently couple the CCD output to the subsequent analog circuit when the result looks very like a conventional television gated DC restoration circuit. This is the method that was used on the NEAR, CONTOUR, and MESSENGER missions, and it is also very suitable for integration into a dedicated processing chip which is the approach we use here.

For these FPUs we are using an Analog Devices AD9807 integrated circuit which performs correlated double sampling, signal amplification, and analog to digital conversion to 12 bits at maximum rates of 6 MHz, comfortably above our rates which are close to 1.5 MHz. This part uses about 100 mA from a single five volt supply. The AD9807 is susceptible to latch up from ionizing radiation in space and to protect it we have added circuitry to remove power and subsequently reset in the event that a latch up occurs. This device is also in a plastic package and these are now starting to be used in space applications when necessary. The CCD output is low enough for the AD9807 amplifier to contribute significant noise, so a low noise wide band operational amplifier is added between the CCD and the correlated double sampler, and the AD9807 is run at low gain.

6.2 Event processing unit

The EPU main function is to control the LORRI instrument via interfaces to the LVPS and IM I/O. The EPU communicates to the spacecraft using an RS-422 link. This link receives commands and transmits engineering data. The EPU uses a RTX2010RH processor, and runs FORTH code. It is similar to units from CONTOUR[3] and MESSENGER, and nearly identical to the unit to be flown on the CRISM instrument on the Mars Reconnaissance Orbiter.

6.3 Imager input/output

The main function of the LORRI IM I/O board is to receive serial image data from the FPU and transmit that data to either of two Integrated Electronics Modules (IEMs) in the required format. Secondary functions include the ability to: store and transmit image header, receive commands from the RTX processor, calculate a 32 bin histogram, generate test patterns without an FPU present, command FPU mode and exposure times based on input from the RTX.

The Imager I/O board contains two field programmable gate array (FPGA) designs. The first is called the imager-interface FPGA. The main function of the imager-interface FPGA is to read images from the FPU and send them to the IEM. There are two image sizes buffered by the IM I/O board. Binned images are 256 x 256, 12 bit pixels and un-binned images are 1024 x 1024, 12 bit pixels. The pixel data format from the FPU is the same regardless of image size, only the number of pixels transmitted is affected. There are two data formats transmitted to the IEM to simplify line addressing for the binned images in the solid state recorder. As an added feature, the IM I/O board can generate test pattern images across the IEM interface without an FPU present. The first pattern consists of a horizontal ramp and the second pattern consists of a vertical ramp.

The imager interface FPGA can also receive data from the RTX. This data is sent across the ASE backplane and through the RTX interface FPGA. The data is used to set the FPU mode and exposure time, set the active IEM low voltage differential signaling port and write the 200 bit header. The FPU mode data is transmitted to the FPU across the pixel data signal at the beginning of each second. The header data replaces the first 25 pixels when data is sent to the IEM.

The second FPGA design on the IM I/O board is called the RTX-bus FPGA. This FPGA calculates a 32 bin histogram of the FPU image data currently being transmitted. This histogram is then made available to the RTX for future exposure time calculations. The RTX FPGA also collects the FPU status and temperature data, making it available to the RTX.

6.4 Low voltage power supply

The LVPS generates 2.5 V, 6 V, and 15 V required by the other boards within the ASE and by the FPU. The input voltage from the spacecraft is 30 ±1 V. It also provides for current, voltage, and temperature monitoring via an I^2C serial interface to the EPU board. The LVPS board provides switching to control power on/off to the FPU and the telescope trim heaters.

6.5 Software

The LORRI instrument's computer shares a common design with PEPSSI and seven MESSENGER instruments. This common design extends into the software. The common software provides packet telemetry and command handling services. Besides handling LORRI-specific packets, the common software automatically generates a variety of standard packets, including housekeeping/status, command echo, memory dump, and alarm packets. Similarly, besides handling LORRI-specific commands, the common software also handles standard commands for memory loads, memory dump requests, etc. The command handling software also provides storage and execution of command sequences. The common software has timekeeping, voltage and current monitoring, and memory management services and a standard boot program.

The LORRI software is 75% common or reused software. The LORRI-specific 25% controls the heaters, collects voltages, currents, and temperatures from the LVPS board, and manages the FPU. In the FPU, the software controls the exposure time, either by manual command or automatically based on the hardware-provided image histogram, generates an image header, and enables routing of the image to the spacecraft. The software also controls the FPU's test patterns and calibration lamps. Whenever the software has nothing to do, it reduces the processor's clock rate to save power.

7. FLIGHT QUALIFICATION

The LORRI instrument was subjected to an environmental qualification program. Performance and environmental testing was performed at both the subassembly and instrument levels. Normally, performance tests or calibrations were done before and after environmental testing.

7.1 Subassembly Test and Calibration

The OTA was tested at the subassembly level by SSG. Wavefront testing was performed using a LUPI operated in double-pass mode. Wavefronts were measured before and after vibration test, and during thermal vacuum test. No change was detected due to the vibration test. Some change was noted at cold temperature during thermal vacuum testing, but it was determined that the level of change was acceptable within our performance requirements. As a secondary verification of performance, modulation transfer function testing was also performed by projecting small features into the OTA, and recording highly magnified images on a non-flight detector. This testing was only performed in ambient conditions. It showed excellent correlation to the wavefront data.

The FPU and CCD were also subjected to testing at the subassembly level. They were calibrated at predicted temperatures, then subjected to environmental testing. The calibration of the FPU and CCD was not repeated after the environmental series due to time limitations.

7.2 Instrument Level Calibration

Instrument level calibration is covered by conference paper 5906B-50[4].

7.3 Environmental Testing

The LORRI instrument was subjected to environmental testing at both the subassembly and instrument levels. Major subassemblies, including the OTA, FPU, and ASE were given vibration and thermal vacuum tests prior to their assembly into the instrument. Electronics packages were powered and operated during both types of test. After assembly into the instrument, vibration and thermal vacuum testing was repeated, with instrument level optical calibration performed both before and after to look for environmentally induced changes. No changes were detected. The instrument was also given an EMI/EMC test, which was also successful. The instrument is now going through environmental testing on the spacecraft.

8. CONCLUSION

The LORRI instrument is currently mounted to the *New Horizons* spacecraft, and continuing to proceed through the spacecraft level environmental series. Several optical tests will be preformed prior to launch, as well as a large amount of electrical testing and mission simulations. Launch is expected in early 2006, with first light on the detector in late 2006.

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