

Development, qualification and integration of the optical fiber array assemblies for the Lunar Reconnaissance Orbiter

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ABSTRACT

The NASA Goddard Fiber Optics Team in the Electrical Engineering Division of the Applied Engineering and Technology Directorate designed, developed and integrated the space flight optical fiber array hardware for the Lunar Reconnaissance Orbiter (LRO). The two new assemblies that were designed and manufactured at GSFC for the LRO exist in configurations that are unique in the world for the application of ranging and LIDAR. Described here is an account of the journey and the lessons learned from design to integration for the Lunar Orbiter Laser Altimeter and the Laser Ranging Application on the LRO.

Keywords: space flight, fiber optic, lunar, altimeter, array, connector, LIDAR, cable, radiation

1. INTRODUCTION

1.1 The Lunar Reconnaissance Orbiter

The LRO is the first in a series of missions towards the exploration of the Moon and Mars for the purpose of providing remote human habitat bases for planetary study.[1] LRO will do extensive mapping of the lunar surface in search of the most appropriate landing sites. The LRO instrument suite will identify resources and explore the environment. High-precision mapping of the moon is a requirement for any future lunar landings. Dr. Farzin Amzajerian of NASA Langley Research Center points out in his recent article published in Photonics Spectra, “Even though Apollo missions targeted well-surveyed landing sites, they still experienced some close calls”.[2] In fact, on page 55 of the 2008 Photonics Spectra July issue, Dr. Amzajerian illustrates just how close the Apollo 14 lunar landing came to a small crater, only inches away from one of its support structure legs. Therefore, the goal of the Lunar Orbiter Laser Altimeter (LOLA), an instrument included in the suite of instruments on LRO, will provide a 3-dimensional mapping of the lunar surface topography for accurate and safe location of future landing sites. LOLA will use a 1064 nm pulsed laser to perform the required altimetry measurements.

1.2 The Longest Laser Link in Space

During the conceptual design of the LOLA instrument, an experiment with the Mercury Laser Altimeter (MLA) Instrument in May 2005, that had launched in 2004, provided the assurance that laser communications could traverse long distances through space. A laser system built and designed at GSFC called “HOMER” [3] located at NASA Goddard’s Geophysical and Astronomical Observatory was used to contact the MLA aboard MESSENGER on its way to Mercury. This experiment established a ranging link across 24 million kilometers, the longest laser link to have ever been performed in space. [4 -5].

1.3 The Lunar Orbiter Laser Altimeter and Laser Ranging

The MLA experimental results were so promising that the Principal Investigators, Dave Smith of NASA and Maria Zuber of MIT, decided that LOLA would not only perform topography mapping of the Moon but would simultaneously make ranging measurements from the Earth while orbiting the moon on LRO, with some instrument enhancements and

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an optical fiber link. This enhancement would be called the “Laser Ranging” mission for LRO and would use a pulsed 532 nm Earth-based laser from the station at Goddard’s facility to LOLA to collect high-precision distance information using the timing of firing-to-receiving at the LOLA instrument. The challenge was to receive the laser pulses with the Laser Ranging Telescope (LRT) located on the end of High Gain Antenna System boom arm while it was pointing at the Earth and transmit the information across 3 subsystems to one of the LOLA detectors. This had to be conducted with a compact but multi-optical fiber configuration. The challenge of the LOLA instrument system was to reduce the size and weight of the previous MLA hardware design from four telescopes into one telescope with the help of a fiber-based array precisely compressed into a single connector.

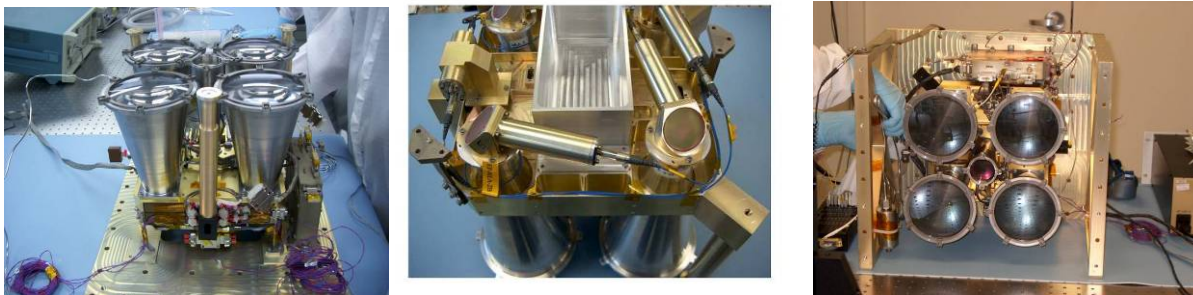


Figure 1: The Mercury Laser Altimeter consisted of four telescopes with fiber coupled from each to four individual detectors.[6]

Where the MLA instrument consisted of four telescopes and was designed to be capable of measuring with a 0.5 m precision, LOLA consists of only one telescope and was designed to produce 0.1 meter precision. Both instruments were designed to measure the planetary reflection timing as a result of firing the short duration pulsed 1064 nm laser aboard. LOLA uses a diffractive optical element on the transmitter to split a single laser beam into five separate beams. On the receiver optics end, a precisely positioned optical fiber array, behind the receiver optics, links each beam to a separate detector. The time-of-flight measurements will provide ranging information. The pulse spreading of the reflected beam will provide information on surface roughness, and the energy of the returned beam will provide surface reflectance. The five spots will provide slopes along and across the orbit track.[1] In addition, to accommodate the “Laser Ranging” from Earth, LOLA detector channel one will be used to monitor the ranging signals from the 532 nm pulsed laser located at the Greenbelt facility. Figure 2 shows an artist’s rendition of the LRO space craft configuration and the LOLA instrument.

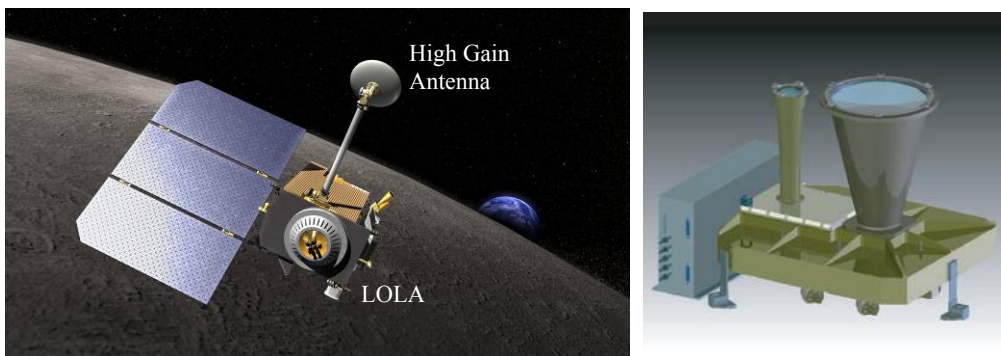


Figure 2: a) Artistic rendition of the LRO with the High Gain Antenna pointing at the earth while instrument LOLA is viewing the moon’s surface, b) Artist’s rendition of LOLA.

2. DISCUSSION

For each of the ranging and altimetry applications, the requirement was that a single array connector be used to couple light from each of the receiver telescopes. Early in development, a modified Diamond AVIM connector was chosen due to its longstanding space flight heritage, a heritage that began with Lockheed-Martin in the 1990s for single mode applications and continued with its usage on the ICESAT Geoscience Laser Altimeter system (GLAS), the Shuttle-Return-to-Flight high definition heat tile sensor camera, and the Mercury Laser Altimeter. For LOLA, Polymicro’s

200/220 micron step index FI series optical fiber was chosen to meet the optical performance requirements, and the 400/440 micron step index FV series optical fiber was chosen for the “Laser Ranging” (LR) application. For LOLA, the requirements dictated five optical fibers be held into a precise alignment pattern with tight tolerances and for LR application, seven fibers were used to provide optimal optical transmission and enhanced reliability.

2.1 LOLA Optical Assembly Design

The solution to the LOLA challenge is pictured in Figure 3, a five fiber array on side A, fanned out to individual standard AVIM connectors on side B. The largest challenge was machining and packaging the pattern on the array side connector ferrule. The tight hole tolerance had to be balanced with the packaging of the fibers into the holes. That is not to say that the termination process was easy; it was indeed not. The process was arduous and time-consuming, with a 50% yield at best once all tests and polishing procedures had been performed. No voids in the epoxy or defects of any kind would be acceptable for these unique space flight assemblies. The ferrules themselves were bought as blanks from Diamond USA/Switzerland and custom drilled in the NASA GSFC Mechanical Systems Engineering Division, Code 540.

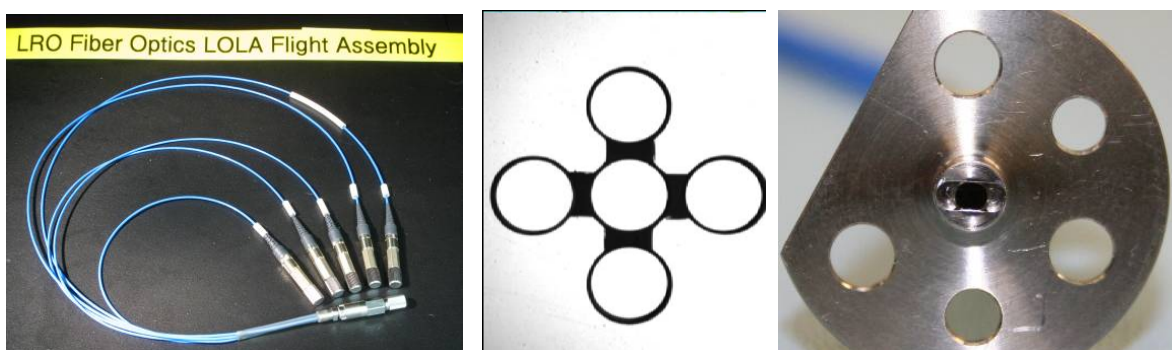


Figure 3 a) LOLA optical fiber array to fan out assembly, b) 200X magnification end face image of optical fiber array, c) the LOLA custom adapter interface to the receiver optics.

In addition to positioning requirements, the LOLA assembly also had very precise length requirements. Each fiber on the fan out side required a different path to its designated LOLA detector, and the detectors were spread around the instrument perimeter. Both for Laser Ranging and LOLA applications, a larger diameter AVIM connector would be required for long-term reliability of the array termination strain relief. For example, the connector spring needed to be enlarged to accommodate the large fibers with the acrylate coating still on. Acrylate coatings are preferred due to the ease of removal with methylene chloride, and chemical stripping is required for space flight terminations. Any scoring or scratching due to tooling could result in latent failure modes that cannot be fixed once the space instrument is launched.

2.2 LOLA Manufacturing and Qualification

The termination procedures used were screened with rigorous requirements validation testing with in-situ transmission monitoring during survival level environmental exposure. The screening details and results are in reference 9. One of the significant lessons learned was related to the vibration levels used for the requirements validation. Early on, the only available information regarding the system-level vibration expectations was through knowledge of the launch vehicle and the appropriate profile as chosen by GEVS[10]. Once the flight hardware was built, the mechanical random vibration levels were larger than expected. The instrument team requested that proto-flight testing – meaning testing on the actual flight articles prior to delivery to the instrument – would be required due to the new design and the elevated vibration levels. In past history, most flight hardware was tested for thermal workmanship levels but not always vibration. In this case, thermal vacuum testing was conducted for eight cycles and two-hour soaks at the extremes with the ramp rate at 30 degrees per hour followed by a random vibration test. Once integrated with the LOLA, the flight articles were vibration and thermal vacuum tested again to instrument set levels. Once LOLA integrated with the entire LRO space craft once again, the assemblies endured vibration and thermal to the space craft thermal and vibration level requirements. So the LOLA integration flight assembly, as a proto-flight article, endured three vibration tests and three thermal vacuum qualification tests.

During manufacturing, screening and qualification, the procedures were drafted into a flow and list of documents for quality controlling the repeatability of the product production. The flight delivery flow is in Figure 4.

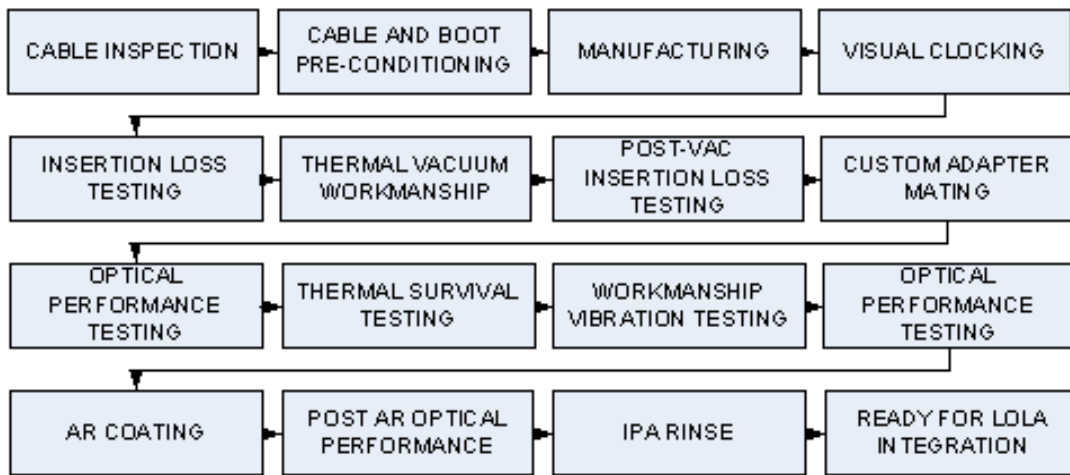


Figure 4: LOLA Optical Fiber Bundle Array Assembly Delivery Flow

As is common practice with all flight assemblies [6], all cables made of fluoropolymers and all connector boots must pass ASTM-E595 as an initial screen and are put through thermal preconditioning. For the hytrel boots on the LOLA assemblies, the preconditioning involves a high-temperature vacuum bake out to ensure compliance to ASTM E595 post processing, and for cables the preconditioning procedure involves thermal cycling in ambient with hour-long soaks at the hot extremes and a half an hour at a cold temperature $\sim -30\text{ }^{\circ}\text{C}$. The survival upper limit requirement for the subsystem is used as the hot thermal extreme during thermal preconditioning, and the cycling is ramped at 1 to 2 $^{\circ}\text{C}/\text{minute}$ for anywhere between 40 to 70 cycles, depending on the cable type. For LOLA, the preconditioning was conducted for 50 cycles using the upper survival thermal limit.[9] Assembly pieces are cut to approximately the length that will be used to maximize the effectiveness of the thermal preconditioning procedure.

2.3 LOLA Bundle Fiber Assembly Quality Documentation

The LOLA bundle assembly included a special mechanical adapter to couple the light from the receiver optics to the bundle array. It was imperative that the clocking be exact such that the reflected five beam image from the lunar surface would align with the fiber array for the highest transmission possible. The clocking of the array was performed visually under a microscope at 200X magnification such that mating to the adapter would be simple. The adapter held the array in a position of 25 microns back from the end of the adapter interface to the receiver optics. The flight adapters ended up on the tight side of the dimensional tolerance, which caused the adapter to fit too tightly on the connector ferrules. Anomaly investigations were performed and proved that the stainless steel ferrules were causing metallic burrs on the tightly toleranced adapter holes, and this resulted in misalignment and difficulty in mating and demating without damage to the arrays. Once the assemblies were properly mated to the adapters, they were not removed. Rigorous processes were put in place to ensure the safety of the unique flight bundle assemblies. The array strain relief was investigated for integrity, and a ferrule compression test was added to the manufacturing procedures to ensure the quality of each array assembly. The compression screen test provided a higher quality on the final product than would be achieved with only the thermal vacuum workmanship testing alone. Figure 5 includes the list of documentation to ensure the quality of the manufacturing, testing and integration of the LOLA bundle array assemblies.

Table 1: LOLA Documentation for Configuration Management

Document Name	CM Documentation Number
LOLA Fiber Optic Flight Assemblies	LOLA-OPTICS-WOA-0338
Thermal pre-conditioning on Flexlite 200/220 μm fibers for flight application	562-PHOT-WI-LOLA-TP-001
Preconditioning Procedure for AVIM Hytrel Boots for LOLA fiber optic assemblies	562-PHOT-WI-LOLA-VAC-001
Procedure for Diamond AVIMS PM Kit Pre-Assemble Inspection	LOLA-PROC-0104
Assembly and Termination Procedure for the Lunar Orbiter Laser Altimeter Five Fiber Custom PM Diamond® AVIM Array Connector for the Lunar Reconnaissance Orbiter	LOLA-PROC-0098
Insertion Loss Measurement Procedure For LOLA 5-Fiber Assembly (Open Beam Configuration)	562-PHOT-WI-LOLA-IL-001
Integration of the LOLA Fiber Optic Bundle to the Telescope Adapter	LOLA-PROC-0140
LOLA Fiber Bundle Inspection and Test Procedure	LOLA-PROC-0099

Once all testing was performed and the assemblies accepted for flight, they were rinsed in isopropyl alcohol to reduce the contamination of the assembly to other parts of the flight instrument suite. Contamination for LOLA was a concern due to the location of the instrument on LRO. Nearby would be an instrument that would be functioning in the UV spectrum where contamination is much more of a problem for the optical systems. Darkening of the optical surfaces can occur from any residues that outgas from nonmetallic materials and condense on the smooth optical interface surfaces. This is the single most common failure mode among laser systems.[10]

2.4 LOLA Optical Fiber Bundle Array Integration.

Several fit checks were performed on the LOLA engineering mock up such that when flight integration time arrived, the flight hardware would fit exactly to the instrument configuration. Integration of the flight hardware occurred in October of 2007. The pictures in Figure 6 show the integration of the flight optical fiber bundle array assembly to the LOLA flight instrument.



Figure 6 a) LOLA flight integration team, including Lead Mechanical Engineer Steve Schmidt, Lead Fiber Optics Engineer Melanie Ott, Quality Assurance Engineer Keith Cleveland, and Optical Engineer Robert Switzer, b) side view of two detectors that were coupled to two channels of the fan out side of the optical bundle assembly, c) LOLA instrument fiber integration complete.

2.5 The Laser Ranging Application

The Laser Ranging assemblies proved much more challenging than the LOLA optical fiber bundles. The main reason was due to the necessity for traversing 3 subsystems which included the boom arm of the High Gain Antenna System, the HGAS gimbals used to steer the antenna, and the long run across the space craft over to the LOLA detector on the opposite end of the space craft. For ease of integration, it was necessary for three cables to complete this set, which implied two optical fiber array-to-array interconnections in precise clocked alignment.

LR Operations Overview

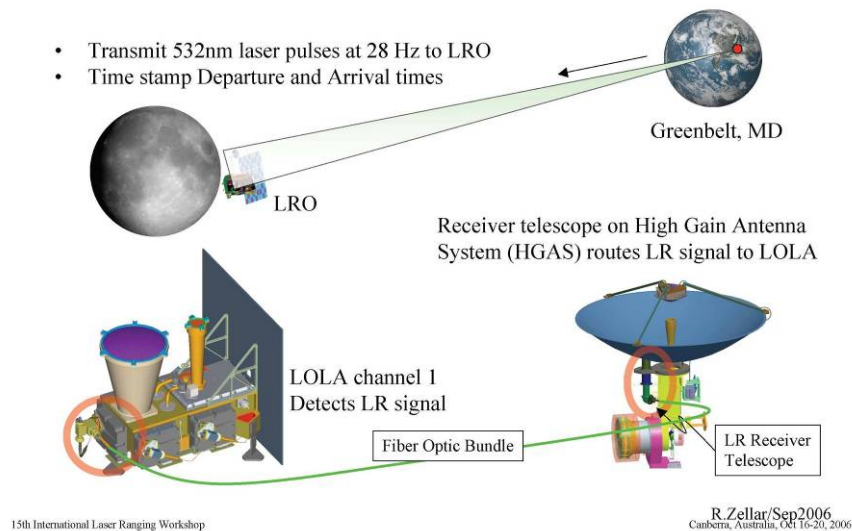


Figure 7: LRO Laser Ranging Configuration Concept [11]

Figure 7 shows the concept as drafted by System Instrument Manager Ronald Zellar during Engineering Peer Reviews for Laser Ranging on LRO and presented at the Laser Ranging Workshop by Dave Smith in 2006.[11] The signal from the Earth is received by the Laser Ranging telescope and routed over from the High Gain Antenna, through the gimbals, down the boom, around a deployment mandrel and over to the LOLA detector channel 1.

LR Flight System Components

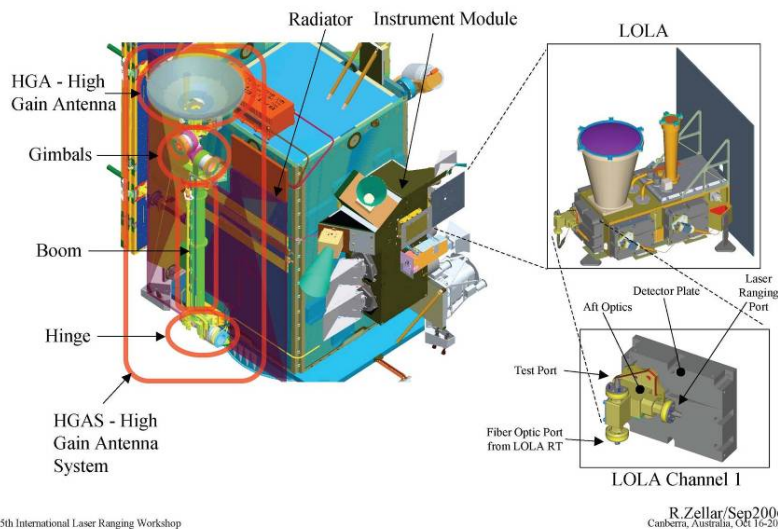


Figure 8: Details on the LRO Optical Fiber Link Path from the LRT to LOLA, D. Smith [12]

In Figure 8, the complexity of the fiber route is represented with greater detail. Since subsystems integration would be complicated and challenging for scheduling, a requirement was set for an interconnection point between gimbals 1 and 2 and another where the entire High Gain Antenna System linked to the space craft on LRO.

2.6 Development of Laser Ranging Application Optical Fiber Bundle Array Assemblies

The Laser Ranging assemblies were designed for enhanced reliability, flexibility and stable performance over a very wide thermal range. Originally, the thermal requirement for the cold limit was $-75\text{ }^{\circ}\text{C}$. Add the cold thermal extreme with all the motion expected from the coiling and uncoiling that occurs inside of the gimbal cable wraps and the deployment hinge and it's clear that to couple enough light reliably would require more than fiber. The optics team chose seven optical fibers at 400/440 microns to provide optimal optical performance while maintaining mechanical flexibility. The ferrules were a concern because again, as with LOLA, the pattern for the fibers had to be precisely centered and within a tight tolerance to be mated to another assembly and minimize the insertion loss.

The largest challenge the team faced was to go from concept to flight hardware in less than two years. The AVIM connector modifications: a larger size to accommodate the large size fibers and clocking ability like polarization maintaining connector predecessors. Diamond Switzerland, along with the Mechanical Systems Division efforts led by Adam Matuszeski at Goddard Space Flight Center, worked the challenges of making the new customized PM AVIM successful. During engineering prototyping, the ferrule material was changed from stainless steel 303 to stainless steel 416 to better accommodate the thermal requirements. Neither of these material types were used with the commercial AVIM connectors, but for ease of the fiber pattern drilling it was the necessary choice to meet the schedule. The custom ferrule drilling was performed both by NASA Goddard and by Diamond Switzerland. For the flight models, the Diamond Switzerland ferrules were used. Figure 9 illustrates the endface pattern and custom drill "flower" pattern.

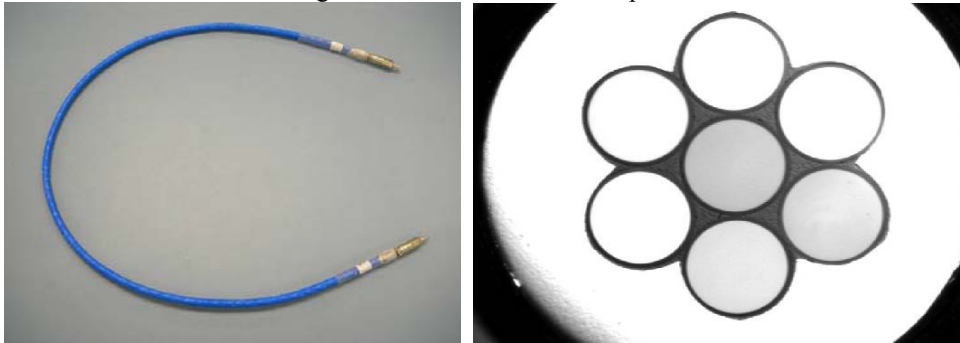


Figure 9 a) Example of a LR seven fiber optical assembly, b) endface picture of Diamond ferrule at 200X magnification with 7 440 micron outer diameter optical fibers packed precisely together to minimize the epoxy bond line.

The optical performance requirements were difficult to meet. Initially, losses at the interconnection locations were complicated by the endface concave polishing conducted such that the arrays would not be in physical contact while real time clocking optimization was performed. The actual adapters used to perform clocking optimization were purposely gapped to avoid any issues with contamination causing gouging or cracking of the optical fiber array during this process. Originally, the low-profile standard AVIM adapter was chosen, but after mechanical difficulties similar to those experienced on LOLA, the Diamond "Cleanable" adapter was used for its ceramic insert that did not experience the scoring that was experienced using a stainless ferrule with the low-profile adapter. In addition, particulates would collect inside of the adapters with repeated mating, and therefore the "Cleanable" version (which could be separated into two parts) was the better choice.

The bundle cable was manufactured to fit the existing cable wraps in gimbal design such that no risk would result from putting an optical fiber harness into the gimbal systems. Considerable effort went into designing the engineering model assemblies to avoid known failure modes and tested with in-situ optical transmission monitoring where possible for:

- Array Compression
- Thermal Vacuum Workmanship, 8 cycles
- Random Vibration Launch Conditions
- Thermal Cycling (accelerated life)
- Cold Gimbal Motion Testing, 20,000 Mechanical Cycles with Active Monitoring
- Gimbal Life Testing, 20,000 Motion Cycles
- Gamma Radiation Exposure

Reference 13 contains the bulk of the data collected on the engineering models that paved the way for the documentation list for the flight bundle assemblies. The list of quality documentation and procedures is presented in Table 2.

Table 2: Laser Ranging Procedures and Quality Documentation

Document Title	Document Number
Thermal Pre-conditioning on Flexlite 200/220 μm fibers for flight application	LOLA-PROC-0137
Preconditioning Procedure for AVIM Hytrel Boots for LOLA fiber optic assemblies	LOLA-PROC-0138
Diamond AVIM PM Kit Pre-Assembly Inspection	LOLA-PROC-0104
Ferrule Polishing & Ferrule/Adapter Matching Procedure	LOLA-PROC-0139
Assembly and Termination Procedure for the Laser Ranging Seven Fiber Custom PM Diamond AVIM Array Connector for the Lunar Reconnaissance Orbiter	LOLA-PROC-0112
Compression Test Procedure for Fiber Optic Connector	LOLA-PROC-0141
Active Optical Power Optimization Procedure for The Laser Ranging Optical Fiber Array Assemblies	LOLA-PROC-0110
Laser Ranging Fiber-Optic Bundle Optical Test Procedure	LOLA-PROC-0107
Insertion Loss Measurement Procedure for The Laser Ranging Optical Fiber Array Bundle Assemblies	LOLA-PROC-0111
Mating of Two LR 7-Fiber Optical Fibers Using Cleanable Adapter	LOLA-PROC-0142
Cutting Back The Kynar Strain Relief For Integration	LOLA-PROC-0143
Fiber Optic Bundle Inspection and Insertion Loss Measurement	LOLA-PROC-0148



Figure 10: Flight Array Bundle Assembly Set

Several anomalies were investigated during the course of the development from the engineering models to the flight models, and as a result the jacketing was removed from immediate contact with the connector. Figure 10 shows the final configuration of the Laser Ranging cable set that was approximately 10 m in length.

2.7 Integration of the Laser Ranging Assemblies

Integration took approximately 9 months and was challenging as expected. Some subsystems were being assembled simultaneously, which made having the necessary resources on hand to accomplish the testing at each location a difficult task. The integration and testing lead, Joanne Baker, made the job much less arduous by keeping the schedule as flexible as possible. The optical fiber assemblies were arranged as such.

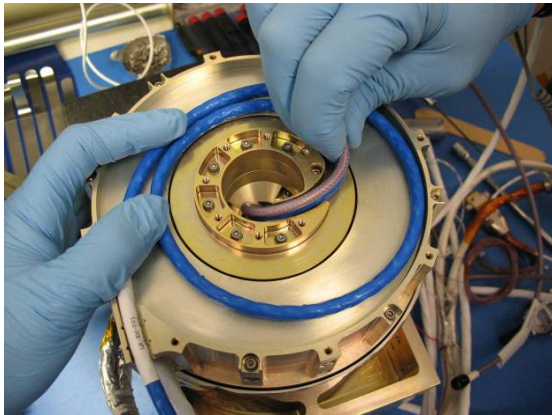
Table 3: Fiber Optic Bundle (FOB) designations and integration locations.

Optical Assembly	Subsystem Link
FOB 1	Laser Ranging Telescope, through Gimbal 1, to the bracket between Gimbals 1 and 2.
FOB 2	Bracket between Gimbals 1 & 2, through Gimbal 2, down the boom, and around the deployment mandrel.
FOB 3	Bracket for the High Gain Antenna System to Detector 1 on LOLA.

The Laser Ranging system was integrated in the following order:

- 1) FOB 2 integrated into Gimbal 2 cable wrap and looped onto boom section.
- 2) FOB 1 integrated into Gimbal 1 cable wrap.
- 3) FOB 1 & 2 interconnected with gimbals 1 and 2 were combined, partial boom segment.
- 4) FOB 2 integrated completely to completed boom and deployment mandrel.
- 5) Gimbals/Boom integrated to the High Gain Antenna.
- 6) LR telescope integrated to High Gain Antenna and connected to FOB 1.
- 7) FOB 3 integrated to Instrument Panel, extra looped aside in preparation for LOLA integration.
- 8) FOB 3 integrated to other side of LRO space craft.
- 9) LOLA integration.
- 10) FOB 3 interconnected to LOLA.
- 11) HGAS integrated to LRO space craft
- 12) FOB 3 interconnected to FOB 2 at LRO space craft bracket.

Before and after every integration operation, optical transmission was monitored and compared to the system level allocations set by lead fiber optics engineer Melanie Ott. Motion testing was run in-situ to monitor performance in the cable wraps of each gimbal during integration. Any exposed cables on the space craft were covered with conducting tape for thermal control such that the cold thermal survival limit could be maintained at -55°C .



Figures 11 a) FOB 2 being routed into the cable wrap on gimbal 2, b) Photonics Group members, Richard Chuska and Robert Switzer work on integration of the FOBs to the gimbal cable wraps.



Figures 12 a) Richard Chuska and Melanie Ott conduct transmission testing on FOB 2 with gimbals now attached to the entire boom arm, b) Melanie Ott and Adam Matuzeski integrate the FOB 2 to a safe position after integration down the boom, while awaiting the mandrel installation.

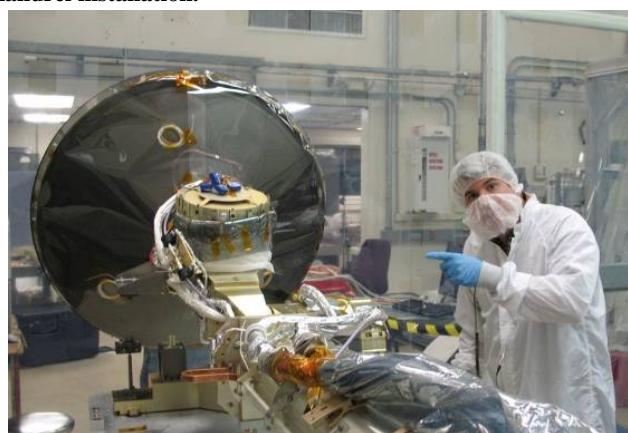


Figure 13a) The team investigates - the full motion of the High Gain Antenna comes close to the optical cable routing configuration. B) Richard Chuska motions that the High Gain Antenna is now fully integrated to the gimbals and boom arm.



Figure 14: a) Richard Chuska, Adam Matuzseski and Melanie Ott watch the motion of the HGA with gimbals running through their full range of motion, b) Melanie Ott routing FOB 3 under the Instrument Module deck

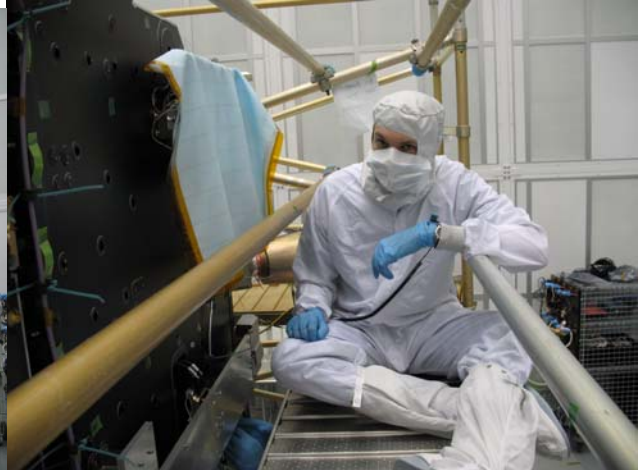


Figure 15 a) William Joe Thomes on second level scaffolding and Richard Chuska routing behind where HGAS will be stowed for launch, b) William Joe Thomes performing FOB 3 routing on the early morning shift before space craft operational testing begins for the day.

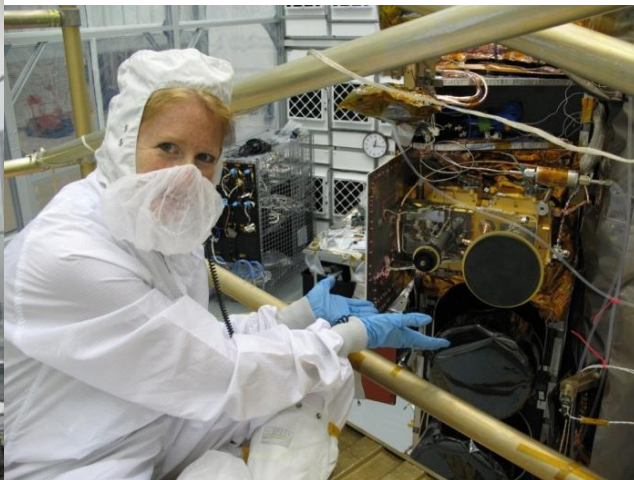
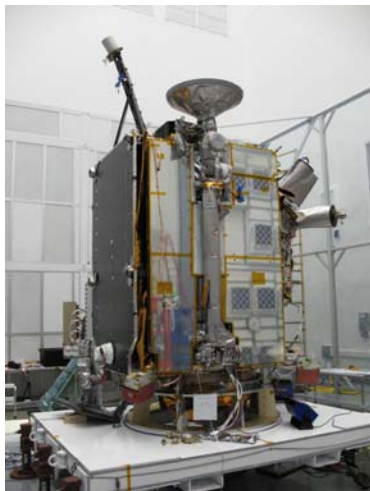


Figure 16 a) LRO fully integrated with the LRT and LOLA systems, b) Melanie Ott pointing out the location of LOLA on LRO

CONCLUSION

Presented here was the journey of developing and integrating the optical fiber assemblies for the Lunar Reconnaissance Orbiter. The array assemblies developed for this space flight mission application are unique in the world. The LRO will be launching in late 2008 and will perform extensive mapping of the Moon, and the laser ranging information will help provide information to enhance the existing gravity model. For more information, please consult the websites <http://misspiggy.gsfc.nasa.gov/photonics>, <http://nepp.nasa.gov>, and <http://photonics.gsfc.nasa.gov>.

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