Space flight qualification on a novel five-fiber array assembly for the Lunar Orbiter Laser Altimeter (LOLA) at NASA Goddard Space Flight Center

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ABSTRACT

A novel multi-mode 5-fiber array assembly was developed, manufactured, characterized and then qualified for the Lunar Orbiter Laser Altimeter (LOLA). LOLA is a science data gathering instrument used for lunar topographical mapping located aboard the Lunar Reconnaissance Orbiter (LRO) mission. This LRO mission is scheduled for launch sometime in late 2008. The fiber portion of the array assembly was comprised of step index 200/220µm multi-mode optical fiber with a numerical aperture of 0.22. Construction consisted of five fibers inside of a single polarization maintaining (PM) Diamond AVIM connector. The PM construction allows for a unique capability allowing the array side to be "clocked" to a desired angle of degree. The array side "fans-out" to five individual standard Diamond AVIM connectors. In turn, each of the individual standard AVIM connectors is then connected to five separate detectors. The qualification test plan was designed to best replicate the aging process during launch and long term space flight environmental exposure. The characterization data presented here includes results from: vibration testing, thermal performance characterization, and radiation testing.

Keywords: Array, connector, spaceflight, vibration, thermal, radiation, qualification, fiber

1. INTRODUCTION

Following in the footsteps of preceding laser altimeter systems, the Lunar Orbiter Laser Altimeter (LOLA) is actually the third generation of lasers altimeters after the initial laser-type altimeter missions MOLA (Mars Orbiter Laser Altimeter) and MLA (Mercury Laser Altimeter) [1]. The LOLA laser signal is split into five separate beam paths when passing through its lens. The five paths are then strategically mapped to five separate tuned detectors on LOLA. The detectors are capable of making over 4 billion measurements over the course of the mission. The instrument itself is capable of distinguishing objects that are at least 50m wide and 1m in height. The returned data will provide a more detailed surface map, including slope and terrain roughness, of the moon then ever before. This information will help guide potential missions for safe landing areas and possible water and ice in deep shadowed regions of the lunar surface.

Based on the heritage of fiber flight hardware for MLA, Diamond connectors were selected and qualified for flight components for LOLA. Instead of four independent fibers with standard Diamond connectors in MLA, LOLA will have the array to fan out assembly with five fibers. The array assembly will basically guide the light receiving from the receiver telescope into the detectors.

The five-fiber array side of LOLA fiber assembly will receive the signal from the receiver telescope and transmit through five single fibers on the fan-out side and aft-optics to five independent detectors. The five-fiber array assembly was constructed of Polymicro Technologies step-index 200/220um optical fiber with 0.22 N.A. inside of the W. L. Gore FLEX-LITE™ cable. Construction consisted of five fibers inside of a single Diamond polarization maintaining (PM) AVIM connector on the array side and fiber individual standard Diamond AVIM connectors on the fan-out side to be connected to five separate detectors.

The most challenging for this LOLA fiber array assembly is how to develop and manufacture robust packaging of five fibers into one Diamond AVIM connector with very tight fiber spacing requirement and precise position of each fiber on the array end face. The five holes pattern was drilled into a stainless steel version of the Diamond AVIM ferrule to be compatible with a PM type connector. The purpose of using a PM connector was to allow the array side to be clocked at a desired angle of degree to a special adapter custom designed by NASA GSFC. Once manufacturing was complete on the engineering models, the qualification of the array assemblies to the LOLA environmental requirements began. The results of vibration, thermal and radiation results are presented here.

2. QUALIFICATION OF LOLA FIBER ARRAY ASSEMBLY

Figure 1 shows a completed manufactured EM (Engineering Model) assembly with an illuminated end-face snap-shot ready to begin qualification testing. Five individual Polymicro 200/220µm fibers were fashioned into a "cross-like" pattern and terminated in a custom manufactured steel ferrule. The custom designed steel ferrule was produced as a joint effort with Diamond Switzerland and GSFC. The five separate fiber fan-outs on the opposite end were terminated with the standard AVIM connector line.

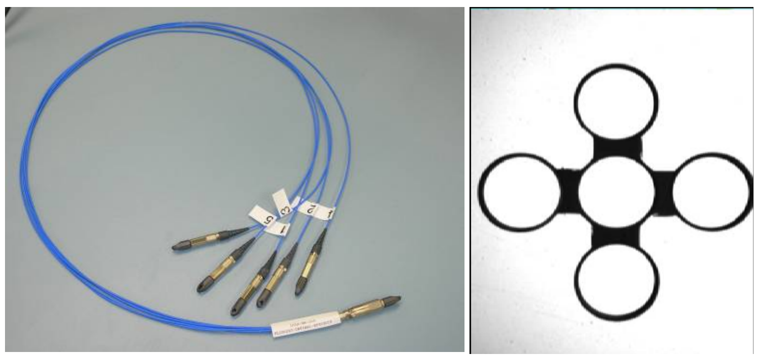


Figure 1: Completed EM LOLA Assembly with illuminated end-face.

Three EM assemblies were selected for a series of tight space flight driven qualification testing: LOLA-EM-008, LOLA-EM-010, and LOLA-EM-011. Each one of the manufactured EM assemblies followed the same proprietary manufacturing procedure and each EM assembly was made from the same "lot" of connector hardware, fiber, and epoxy for consistency and tracking. Carefully planned random vibration and thermal cycling tests were conducted on the LOLA EM assemblies to verify the assemblies will survive a typical space environment. Channel #1 of the fan-out side was originally terminated with Hytrel right angle boot and the other four channels were terminated with standard Hytrel straight boots. It was determined later that the right angle boot would sit to be high off the instrument itself and may pose a potential snag problem. The length of each EM assembly is listed in Table 1.

Table 1: The length of LOLA EM Assembly

Assembly ID #	Length
LOLA-EM-008	0.75m
LOLA-EM-010	0.75m
LOLA-EM-011	0.74m

3. RANDOM VIBRATION CHARACTERZATION

A random vibration profile for optical connector testing, normally set to be at least twice the vibration requirement of the launch vehicle, was entered into the vibration controller. The detailed profile totaling 20grms is listed in Table 2. This profile is used for testing the x, y, and z axis on a custom machined connector holder which fits the dimensions of the vibration drum. Each axis was then tested for 3 minutes in duration. While the 3 minute test was conducted power monitoring was recorded using a LabVIEW based data recording as well as a high resolution recording microscope for later detailed investigation of the connector performance.

Table 2: Random Vibration Profile

Frequency (Hz)	Acceleration Spectral Density Levels
20	.052 g^2/Hz
20-50	+6 dB/Octave
50-800	.32 g^2/Hz
800-2000	-6 dB/Octave
2000	.052 g^2/Hz
Overall	**20.0 grms**

2.1 Random Vibration Testing Setup

An open beam type configuration setup was used to test the LOLA EM assemblies to better simulate actual application and conditions within the mission. A high resolution microscope called the ProScope by Bodlein was used to catch and log snap-shot images before, after, and during vibration. Once the vibration test was complete the two images before and after vibration were digitally overlapped to verify any permanent shift, rotation, or displacement of the fiber end-faces. In Figure 2 a 660nm visible light LED was connected to a 1x12 splitter and mated to the standard AVIM connectors on the fan-out side of the cable. The LOLA assembly was mounted on a custom designed vibration fixture. The five standard AVIM connectors on the fan out side were taped down on the fixture plate and the custom AVIM PM connector on the array side was mated and assembled to a custom made LOLA slotted adapter. The custom made LOLA adapter was designed to mimic the type of adapter that will be used on the entrance of the telescope. The vibration fixture was mounted on the vibration drum using four Allen stand-off screws. The ProScope was set up next to the vibration drum to catch the images and movies of fiber end-face on the array AVIM connector before, during, and after the vibration. The vibration drum was driven by the control signals fed through a signal amplifier. A calibrated accelerometer mounted to the fixture was connected to the controller to complete the feedback loop. The controller monitors the output from the accelerometer and will adjust the intensity of the output signal to the vibration drum in reference to the input of the programmed profile.

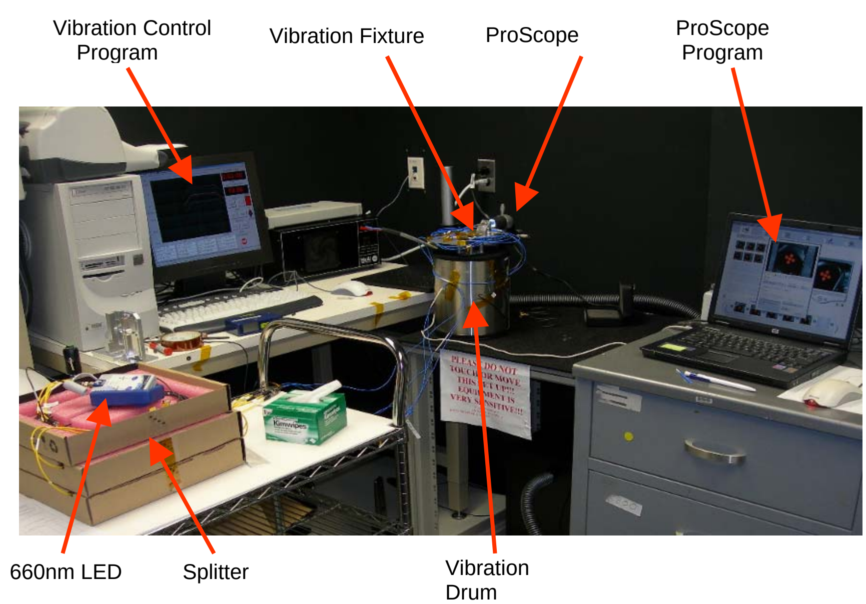


Figure 2: Setup of Random Vibration Testing on LOLA EM Assemblies

2.2 Random Vibration Testing Results:

Two types of pass or fail criteria was used to evaluate the results of the LOLA assemblies (Table 3 and 4). The first criteria used the digital overlapping images of before and after vibration to verify any shift, rotation, or moving of fiber end-faces on the array connector. The second criteria used the insertion loss measurement comparisons of each fiber channels before and after vibration to show any significant changes.

Table 3: Summary of Vibration Testing on LOLA EM Assemblies

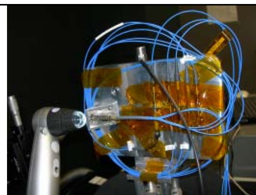
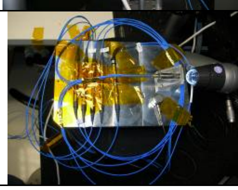
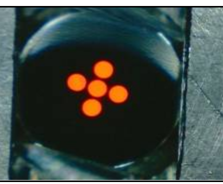
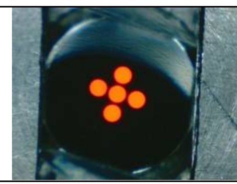
LOLA EM Assembly	Assembly Testing Layout	Image Before Vibration	Image After Vibration	Overlapped Image before and after vibration
LOLA-EM-008 X-axis				
Y-axis				
Z-axis				

Table 4: Insertion Loss Measurement in dB of Vibration Testing on LOLA EM Assemblies.

LOLA-EM-008:

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5
Pre-Vibe	0.51	0.33	0.15	0.59	0.46
Post-Vibe	0.43	0.32	0.19	0.42	0.37
Δ (IL)	-0.08	-0.01	0.04	-0.17	-0.09

LOLA-EM-010:

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5
Pre-Vibe	0.39	0.35	0.28	0.32	0.29
Post-Vibe	0.39	0.34	0.31	0.28	0.26
Δ (IL)	0	-0.01	0.03	-0.04	-0.03

LOLA-EM-011:

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5
Pre-Vibe	0.41	0.36	0.42	0.45	0.45
Post-Vibe	0.34	0.35	0.34	0.42	0.38
Δ (IL)	-0.07	-0.01	-0.08	-0.03	-0.07

Table 3 shows only the images for the assembly LOLA-EM-008. The last column in the Table 3 shows that two end-face images before and after vibration. In each case the overlapped images observed no shift or rotation anomalies. The comparison of the insertion loss measurements before and after vibration in the Table 4 showed that most channels had some small gains in transmission, possibly due to improved alignment in the adapter during vibration, and the vibration induced insertion losses were not more than 0.1 dB.

3. THERMAL CYCLING CHARACTERZATION

The thermal cycling test was used to see if the LOLA EM assemblies would survive and maintain an acceptable amount of transmission when exposed to the long-term thermal stresses of the expected environment. The thermal profile was from -30°C to +60°C for a total of 60 cycles at 2°C/minute ramp rate with 30 minute soak times at both extremes.

3.1 Thermal Testing Setup:

Similar to vibration testing setup, an open beam configuration was used (Figure 3). A white light lamp was used as the light source, which has two arms, and one was used as the signal source input and the other as the reference to monitor the signal source variations. The three AVIM connectors of three LOLA EM assemblies were mounted and fixed together on the holder as seen in Figure 4. The signal source arm was mounted and routed to shoot a beam through the chamber window glass into the three array AVIM connectors simultaneously. The AVIM connectors on the fan out side were connected to reference cables which were fed through the chamber hole and mated to Agilent 8166A multi-channel power meters. Due to the limitations of the Agilent 8166A detector only four fiber channels from each assembly were actively monitored and recorded once per minute using the LabVIEW acquisition program. A thermal coupler was mounted near the assemblies to record the temperature cycling of the thermal chamber.

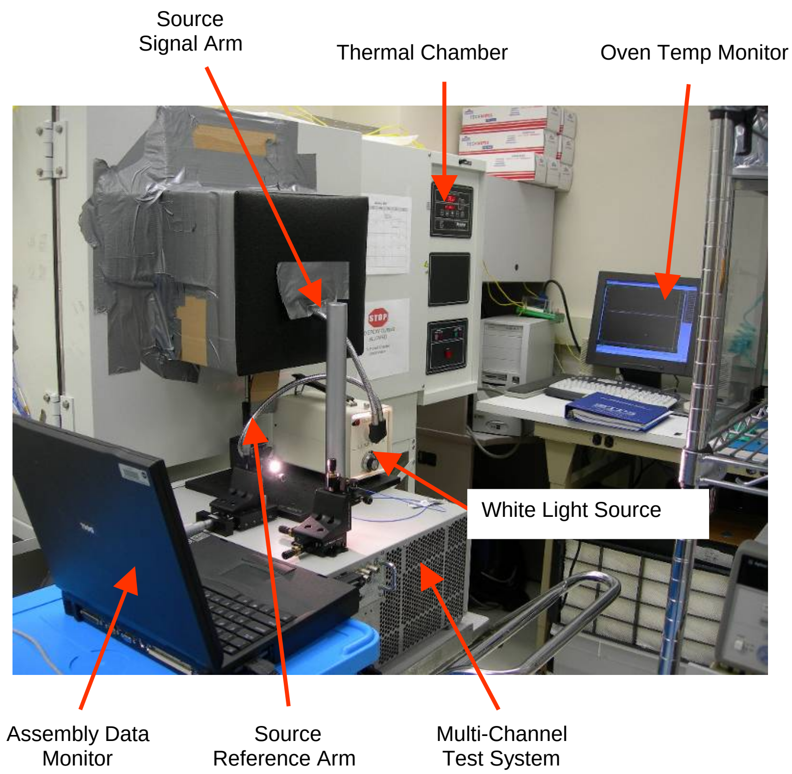


Figure 3: Setup of Thermal Cycling Testing on LOLA EM Assemblies

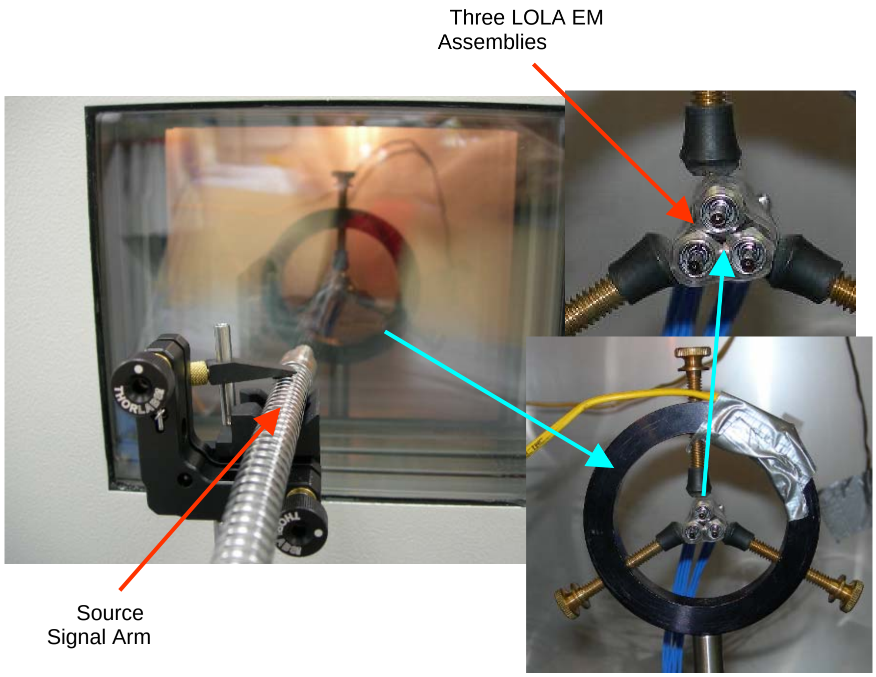


Figure 4: Setup of Three LOLA EM Assemblies in Thermal Chamber

3.2 Thermal Testing Results:

Figure 5 shows the in-situ data plot of the thermal cycling test on all three LOLA fiber assemblies. The white source lamp broke at the 45th cycle and a new lamp was quickly replaced for the rest of the testing cycles. Insertion losses for all channels were below 0.4dB with the exception of channel #4 of the assembly LOLA-EM-010 which was 0.6dB. Just like in the vibration test, insertion losses were measured on all actively monitored channels before and after the testing. These measurements were compared and the insertion losses were not more than 0.1dB, as shown in Table 5.

Table 5: Insertion Loss Measurement in dB of Thermal Cycling Testing on LOLA EM Assemblies

LOLA-EM-008:

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5
Pre-thermal	0.43	0.32	0.19	0.42	0.37
Post-thermal	0.42	0.2	0.16	0.36	0.31
Δ (IL)	-0.01	-0.12	-0.03	-0.06	-0.06

LOLA-EM-010:

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5
Pre-thermal	0.39	0.34	0.31	0.28	0.26
Post-thermal	0.43	0.4	0.35	0.28	0.26
Δ (IL)	0.04	0.06	0.04	0	0

LOLA-EM-011:

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5
Pre-thermal	0.34	0.35	0.34	0.42	0.38
Post-thermal	0.35	0.34	0.38	0.37	0.4
Δ (IL)	0.01	-0.01	0.04	-0.05	0.02

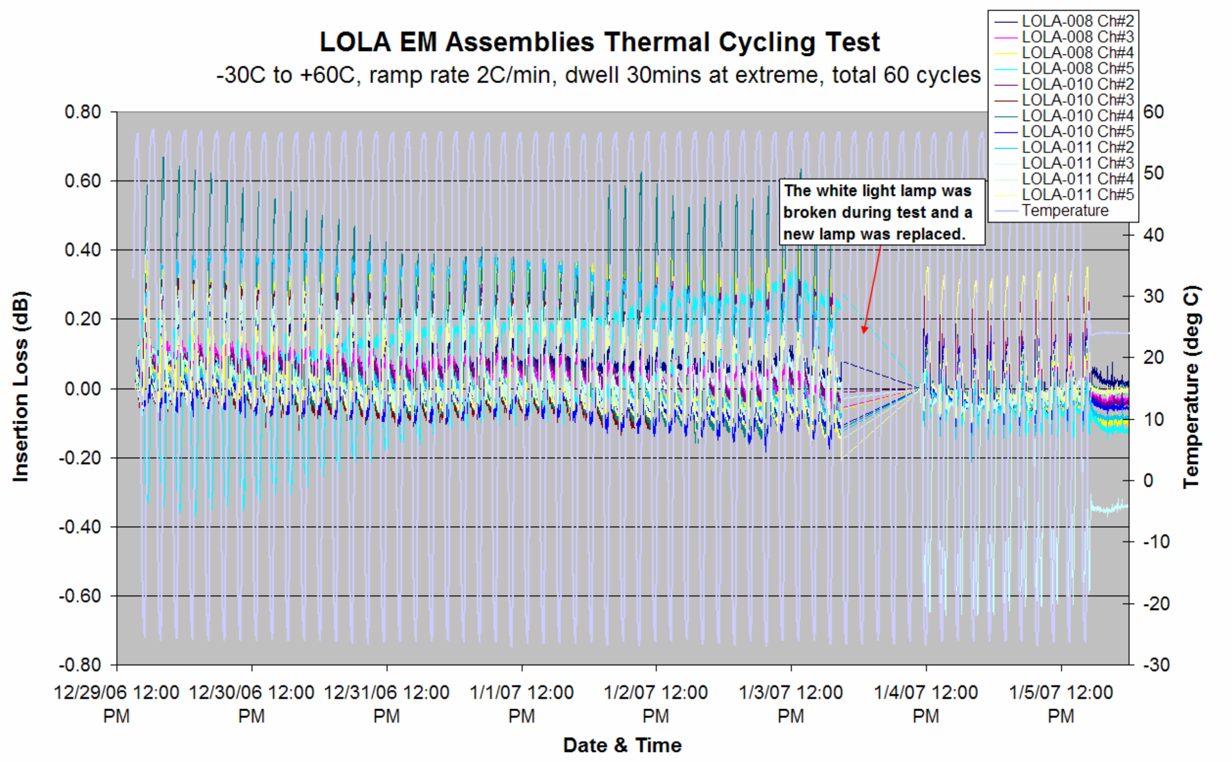


Figure 5: Thermal Cycling Test Data Plot on Three LOLA EM Assemblies

4 LOLA FIBER RADIATION CHRACTERZATION

To simulate a space flight radiation environment, a gamma (Cobalt 60) radiation chamber was used for testing the LOLA fibers. The test focused on transmission effects at different radiation dose rates. The radiation chamber selected for this portion of the testing is located at NASA Goddard Space Flight Center. The Co60 chamber at GSFC has a couple of unique features. One feature is the Co60 gamma source is in a room. Another unique feature is there are two sources located inside the room. One source, labeled the Low Dose, is estimated at 18 rads/min and the High Dose is rated on the order of 152 rads/min. Two 10m long fiber spools were cut and terminated with FC connectors as well as 15m lead in and out cables. Gamma radiation exposure was monitored at two discrete dose rates for an uninterrupted 2.5 week time period.

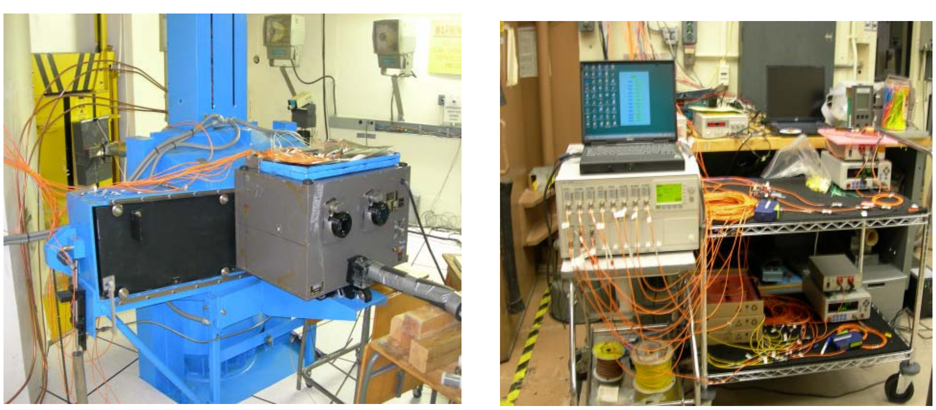


Figure 6 (a; b): Thermal Chamber Positioned in Front of Co60 Source and Data Gathering Setup

4.1 Radiation Test Setup

Because this testing was performed along with some Sandia National Laboratory flight fiber cable qualification tests [2], one 10m fiber spool was mounted on the thermal chamber front door directly in front of the High Dose radiation source. This was to done in order to achieve a dose rate of 152rads/min at room temperature, however, the actual temperature for this fiber was 9.6ºC due to the thermal chamber trying to maintain -25°C temperature set point. The other fiber was placed in front of the Low Dose radiation source to achieve a dose rate of 18.2rads/min. In order to monitor the equipment inside the gamma radiation chamber properly and efficiently, 15m reference cables were used to connect the UUT spools to Agilent 8166A power meter and the optical power sources. The reference cables were routed in such a way to be out of direct radiation exposure. Figure 5(b) shows the testing setup outside the radiation chamber used to monitor the radiation effects of the UUT spools. The optical power was attenuated to be less than 1uW CW at 850nm to limit any possible photo-bleaching effects. Power measurements were captured every 1 minute from the Agilent 8166A with LabVIEW acquisition programming. The power monitoring actually began a few minutes before the radiation began in order to capture any initial dose effects that could have happened. The LED source was monitored during the duration of the test and the power drift was subtracted out of the final data calculation.

4.2 Radiation Testing Results

Table 6 summarizes the total dose, dose rate, and temperature condition for each 10m fiber spool. The radiation testing was conducted for approximately 385 hours. After which, the thermal chamber returned to room temperature and the fiber was still exposed to radiation for an additional 48 hours. Once the radiation portion was completed the experiment was immediately relocated to the Photonics lab and testing continued to gather additional recovery data during the annealing process.

The objective for the radiation test was to expose the fibers simultaneously to two different dose rates at room temperature. However, the fiber placed on the outside of the thermal chamber door was unexpectedly exposed to a colder temperature of 9.6ºC. Figure 6(a) represents radiation-induced attenuation for the fiber spool #1 at high dose rate of 152rads/min at two different temperatures. As expected, Figure 6(b) fiber spool #2 shows the cold temperature data curve at a higher radiation induced attenuation than at the expected room temperature curve.

Table 6: Radiation Testing Parameters

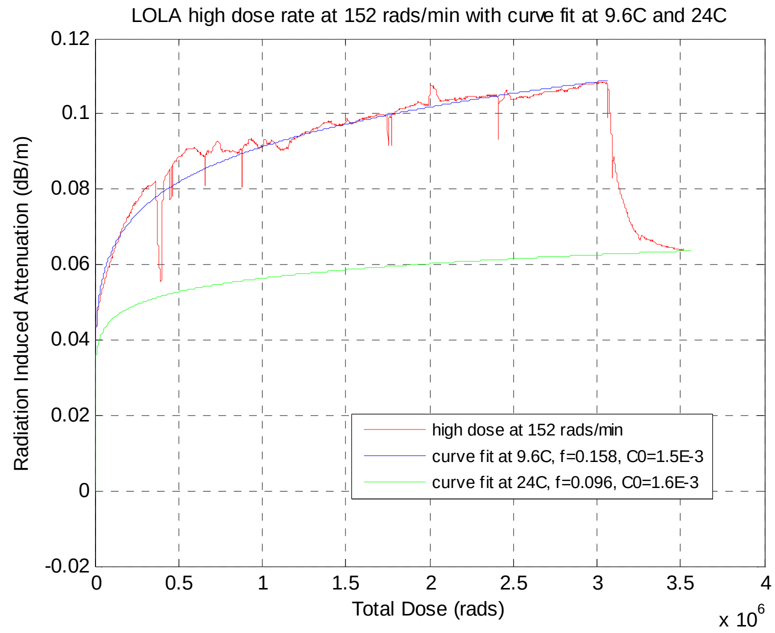
Cable ID	Dose rate (rads/min)	Total dose(Krad)	Cable Length	CableTemp
Cable 1	152	3511	10m	9.6ºC
Cable 2	18.2	420	10m	24ºC

Mathematical data processing software called MatLab was used to process the collected data. The Friebele Model was chosen as the extrapolation method [3]. Using this extrapolation method, the equation for radiation-induced attenuation in optical fiber takes the form:

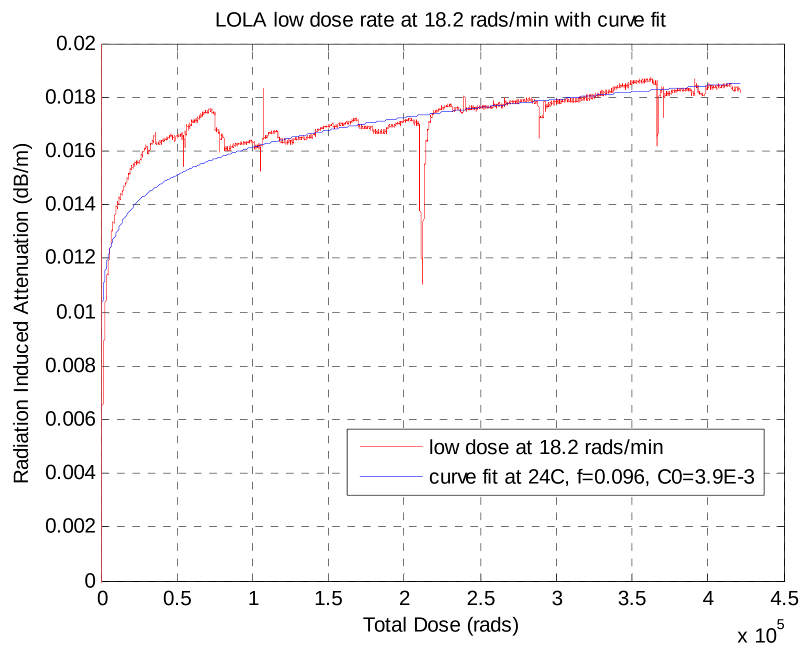
$$A(D)=C_0\phi^{1-f}D^f \qquad (1)$$

A (D) is the radiation induced attenuation, D is the total dose, ϕ is the dose rate, C_0 is a constant, and f is a constant less than one. The radiation test on cable 1 had a high dose rate of 152 rads/min which translates to $A(D)=1.5 \times 10^{-3}\phi^{(1-.158)}D^{.158}$(dB/m) with a curve temperature fit of 9.6ºC. The radiation test on cable 2 had a low dose rate of 18.2 rads/min which translates to $A(D)=3.9 \times 10^{-3}\phi^{(1-.096)}D^{.096}$(dB/m) with a curve temperature fit of 24ºC. Based upon the model equation (1) no general model can be derived without making some assumptions about the constants C_0 and f [3, 4]. Two sets of data are necessary to determine which C_0 and f should be used for extrapolation to other dose rates at different temperatures. Under the assumption that f is a linear function of temperature T and C_0 is a linear function of dose rate ϕ, the general model for other dose rates and other temperatures can be made using two data sets. Solving for f (T) using both data sets, the expression is

$$f(T) = -4.3 \times 10^{-3}T+0.1993 \qquad (2)$$



a)



(b)

Figure 7: LOLA Fiber Cable Radiation-Induced Attenuation Data
a) At 152 rads/min exposure with curve fit
b) At 18.2 rads/min exposure with curve fit

At room temperature of 24ºC, f = 0.096, and $C_0 = 1.6 \times 10^{-3}$ at 152 rads/min and $C_0 = 3.9 \times 10^{-3}$ at 18.2 rads/min. Solving for $C_0(\phi)$ using both data sets, the expression is

$$C_0(\phi) = -1.72 \times 10^{-5}\phi + 4.21 \times 10^{-3} \quad (3)$$

Using equation (3), dose rate becomes very small or less than 1 rad/min which is typical of space flight background radiation, C_0 becomes 4.21×10^{-3}, independent of dose rate. Under this assumption that most space flight environments have background radiation at levels less than 1 rad/min, the expression for radiation-induced attenuation at room temperature of 24ºC can be described as:

$$A(D) = 4.21 \times 10^{-3}\phi^{1-0.096} D^{0.096} \quad (4)$$

Equation (4) represents the extrapolation model equation derived for LOLA fibers at room temperature.

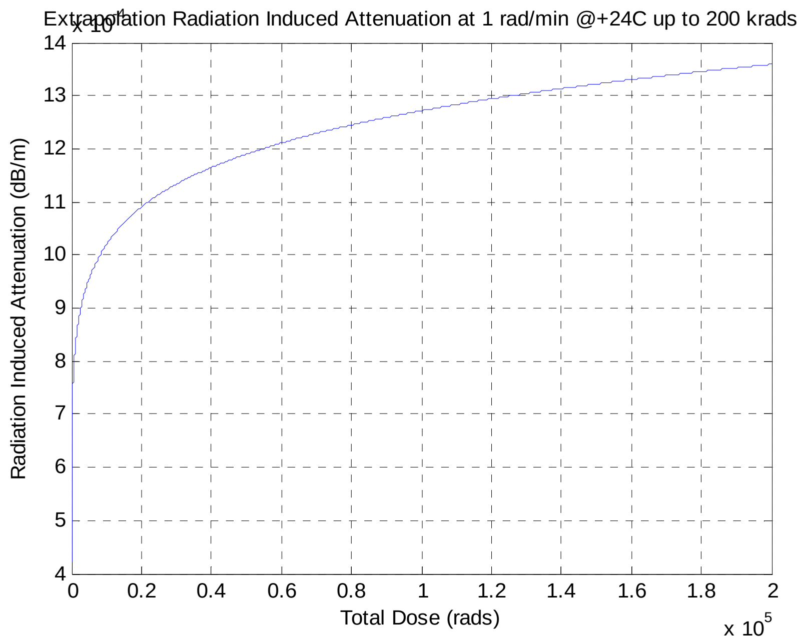


Figure 8: Extrapolation Curve at the dose rate of 1 rad/min up to 200 Krads at temperature of 24ºC

5 CONCLUSIONS

A novel multi-mode 5-fiber array assembly was developed, manufactured, characterized and then qualified for the Lunar Orbiter Laser Altimeter (LOLA), a science data gathering instrument aboard the Lunar Reconnaissance Orbiter (LRO) mission. Three carefully organized qualification tests were chosen for validation: random vibration, thermal cycling, and radiation exposure. All tests were preformed on three identically manufactured fiber optic cable assemblies.

During vibration testing, two images were taken one before and one after vibration. Each assembly's image was then digitally overlapped to verify any shift, rotation, or moving of fiber end-faces. Then, insertion loss of each fiber channel from before and after vibration was measured and compared for any unexpected changes. Most channels had shown small gains in transmission, possibly due to improved alignment in the adapter during vibration, and the vibration induced insertion losses were not more than 0.1dB.

Thermal cycling testing was conducted on all three assemblies from -30ºC to +60ºC for 60 cycles total at 2ºC/minute ramp rate and 30 minute soaks at the two extremes. The optical transmissions of 12 selected channels, four fiber channels from each assembly, were actively monitored and recorded once per minute. The insertion losses were measured before and after the testing and showed not more than 0.1dB delta between the two.

LOLA fibers were tested and characterized for gamma (Cobalt 60) radiation to simulate the expected space flight environment. Two 10m long fiber spools were selected for gamma radiation exposure at two discrete dose rates. Both spools were expected to be at room temperature for an uninterrupted period of time, but minor complications in the test setup early on adjusted one of the spools temperatures to be 9.6°C. This complication caused a slight shift in attenuation due to the temperature decrease, but the data was still valid. Finally, the extrapolation model was derived for the LOLA fibers under space flight background at levels less than 1rad/min at room temperature.

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