Space flight requirements evaluation testing on the 7 optical fiber array connector/cable assemblies for the Lunar Reconnaissance Orbiter (LRO)

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ABSTRACT

In the past year, a unique capability has been created by NASA Goddard Space Flight Center (GSFC) in support of Lunar Exploration. The photonics group along with support from the Mechanical Systems Division, developed a seven fiber array assembly using a custom Diamond AVIM PM connector for space flight applications. This technology enabled the Laser Ranging Application for the LRO to be possible. Laser pulses at 532 nm will be transmitted from the earth to the LRO stationed at the moon and used to make distance assessments. The pulses will be collected with the Laser Ranging telescope and focused into the array assemblies. The array assemblies span down a boom, through gimbals and across the space craft to the instrument the Lunar Orbiter Laser Altimeter (LOLA). Through use of a LOLA detector the distance between the LRO and the Earth will be calculated simultaneously while LOLA is mapping the surface of the moon. The seven fiber array assemblies were designed in partnership with W.L. Gore, Diamond Switzerland, and GSFC, manufactured by the Photonics Group at NASA Goddard Space Flight Center (GSFC) and tested for environmental effects there as well. Presented here are the requirements validation testing and results used to insure that these unique assemblies would function adequately during the Laser Ranging 14-month mission. The data and results include in-situ monitoring of the optical assemblies during cold gimbal motion life-testing, radiation, vibration and thermal testing.

Keywords: Optical, Fiber, Array, LIDAR, Ranging, Connector, Spaceflight, LRO, LOLA, Qualification

1. INTRODUCTION

The Laser Ranging (LR) mission was an add-on to the LRO soon after it was demonstrated that laser pulses between the Mercury Laser Altimeter, a previous NASA GSFC Instrument launched in August 2004, could span over 24 million kilometers of space to the station at Greenbelt MD and back.[1-2] The motivation behind precise distance measurements between the LRO and the earth is to enhance the existing gravity model by the Principal Investigators David Smith and Maria Zuber. The challenge was how to get light from earth based laser pulses over to the other side of the LRO to a detector based on the LOLA instrument while it simultaneously was focused its laser and receiver optics on the moon. The solution was to use a long fiber optic cable to move the light from the LR receiver telescope across the X-Y High Gain Antenna System (HGAS) gimbals, down the HGAS boom, across a one-time deployable mandrel, then around the other side of the space craft to a LOLA detector. The total distance is less than 10 meters but under, bending constraints, cold temperatures and motion. The seven fiber bundle design was investigated and due to the high performance requirements, the decision to use the fiber bundle along with a Custom Diamond AVIM optical fiber connector was made early during design. The seven hole pattern was drilled into a stainless steel version of the Diamond AVIM ferrule to be compatible with a slightly larger polarization maintaining (PM) type connector. The purpose of using a PM type of connector was for the purpose of interconnection of fiber bundle assembly to fiber bundle assembly. The effort continued through development since November of 2005 and is currently in flight integration on the LRO. The following details the testing and lessons learned while developing the optical fiber bundle assemblies for the Laser Ranging mission on LRO.

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2. EXPERIMENTAL DISCUSSION

The Laser Ranging application required a total of three cables to allow ease during integration with several subsystems. The subsystems are the gimbals, the HGAS boom arm and the LRO space craft. Due to the necessity of three assemblies, the interconnection between those assemblies required special attention. The optical fiber array connector ferrules were a key item for focus in regards to regulating the insertion loss at those interfaces. In addition, for reliability, the termination procedure was a high focus area as well.

The fiber used for the bundle was manufactured by Polymicro Technologies and the FON 1416 cable was manufactured by W.L. Gore. The fiber ferrules were made of stainless 416 and are Diamond Switzerland drawing number 070-040-230V001_55; the Custom PM connector kit is Diamond D 6206.6/S NASA 1036529. The custom ferrules were drilled using a GSFC designed flower pattern, and the drilling was conducted at GSFC and at Diamond Switzerland. The cable was made of seven flexlite cabled optical fiber strands wrapped and twisted around a PTFA buffer strand approximately the same outer diameter of the flexlite cable. The entire set of 7 flexlite cables are upjacketed with Gore Tex wrap followed by a PFA outer jacket. The first version of the cable bundle (FON 1416) consisted of a twist of the flexlite strands 360 degrees around the middle buffer every 3 inches which resulted in a very high insertion loss ~0.4 dB/m, likely due to microbending stresses. When the bundle manufacturing design was changed to an 18 inch twist configuration, the insertion loss reduced to 0.07 dB/m. The Diamond low profile adapter was included in the design for interconnecting the bundles.

Qualification testing for the fiber bundle array assemblies included cable preconditioning testing, repeatability testing of the connector interface, vibration testing, thermal cycling, gimbal life cold motion testing, routing-bending testing and radiation testing. The LR assemblies were tested in sets of three as similar to the actual application as possible. Figure 1 shows three bundle array assemblies mated together to make the complete LR set. Figure 2 shows an earlier version of a single bundle array assembly showing the configuration of the end faces in that assembly. The end face pictures in Figure 2 show how each of the ferrules was cut into a custom "flower" pattern to accommodate the outer diameter of each outer fiber and the inner fiber while limiting the amount of epoxy necessary.

Figure 1: Three Flight LR Bundle Array Assemblies Mated Together

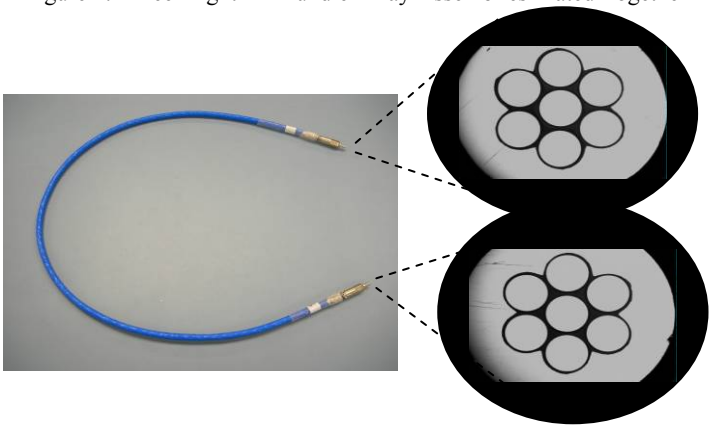


Figure 2: LR Fiber Optic Bundle Array Assembly with End Face Pictures.

The three assemblies were cut to length per the length requirements for the space craft integration. The assemblies were terminated and verified for adequate optical performance. Prior to termination, thermal preconditioning was performed on the cable bundle and the connector ferrules were inspected for proper specification dimensions. At the time of this testing, the ferrules were still slightly out of specification since the fine tuning of the custom drilled flower pattern was still underway. However, the testing data provided here was not meant to provide absolute loss values but relative values such that reliability would be assured and delta insertion loss values could be set for system level allocations and analysis. The cable assemblies were clocked to match reference assemblies such that when two bundle array assemblies were mated together they were optimized for maximum power throughput for the majority of the fiber channels.
Due to the need to monitor all channels, there are two extra fiber interfaces in the testing set up in addition to the two interconnections required for the mission. The actual application will have an open beam on the input (receiver telescope) with an open beam detector (at LOLA) on the output and both are adjustable for system optimization. All insertion loss test set ups have an additional interconnection for in lab testing. Therefore, compared to the actual implementation, the in-lab measurements over-estimate the performance insertion loss. Table 1 summarizes the lengths and insertion loss of the test sets for environmental characterization.

Table 1: Laser Ranging Engineering Model Test Cable Assembly Set Lengths and IL

DUT Sets	Assembly ID #	Length (m)	Average IL for Set @ 532
SET 1	LR-EM-008	1.59	2.0 dB
	LR-EM-004	2.87	
	LR-EM-010	3.80	
SET 2	LR-EM-011	1.56	2.7 dB
	LR-EM-009	2.70	
	LR-EM-007	3.72	

2.1 Thermal Preconditioning

The outer jacket of the FON 1416 was made of a PFA Teflon in which GSFC had no thermal preconditioning data. A typical profile was used where depending on the cable type and thermal environment, 60 cycles usually eliminates a majority of the cable material shrinkage such that the cable shrinks no more than 0.1%.[3] The upper thermal limit was based on the system level survival thermal requirement. Thermal requirements for the Laser Ranging fiber optic assemblies were set to -55°C to +80°C for survival, and -45°C to +70°C for operational. For operations involving motion such as in the gimbals, the lower limit is -20°C for survival and -10°C operational. Based on the requirements the thermal preconditioning limits were set to -30°C to +80°C with dwells at the lower temperature of 30 min and at the upper limit of 60 min. During the preconditioning study it was determined that even after 80 cycles, the cable PFA outer jacket would not reach the 0.1% limit. With a twist of the cables, less often at 18 inches as opposed to 3 inches, the flexlite cables would not move the same amount length-wise during cable flexing. The 3 inch twist had provided a sturdy design for flexing, although highly lossy. Therefore, the problems that arose during the termination and testing procedures led us to believe that the bundle jacketing needed to be removed from the terminated connector.

2.2 Repeatability Testing

The team had concerns for integration since there would be many opportunities for the hardware to be mated and unmated. Several times during the development, mating repeatability tests were conducted to gather data on the insertion loss changes expected as well as assure that the system would perform reliably during integration. The assemblies were inserted into an adapter such that the two mated and the insertion loss was monitored over thirty matings. During testing of the brass low profile adapters, the losses never exceeded 0.15 dB provided the adapters were cleaned once when the fit became too tight.

2.3 Vibration Testing

Random vibration testing was conducted on two LR sets that consisted of three assemblies each. Three axis testing was conducted using three different profiles for 3 minutes per axis. The vibration profile used for each test is contained in Table 2.[4]

Table 2; Random Vibration Acceleration Spectral Density (ASD) Levels VS. Frequency

	Test 1: ASD levels	Test 2 ASD levels	Test 3 ASD levels
Frequency Range (Hz)			
20	.052 g^2/Hz	.026 g^2/Hz	.013 g^2/Hz
20-50	+6 dB/Octave	+6 dB/Octave	+6 dB/Octave
50-800	.32 g^2/Hz	.16 g^2/Hz	.08 g^2/Hz
800-2000	-6 dB/Octave	-6 dB/Octave	-6 dB/Octave
2000	.052 g^2/Hz	.026 g^2/Hz	.013 g^2/Hz
Overall	20 grms	14.1 grms	10 grms

The three profile test program was designed to simulate all the vibration exposure opportunities that would occur from system level integration through launch. During testing the cable assembly set is monitored in-situ at 850 nm to eliminate system noise from the test results and to monitor for any damage as it occurs. The other before and after testing is performed at 532 nm on a separate test set up and does include noise related to changing testing set ups and end faces are inspected post testing to ensure no cracking of the fiber had occurred. Figure 3 is a picture of the testing set up with in-situ monitoring.

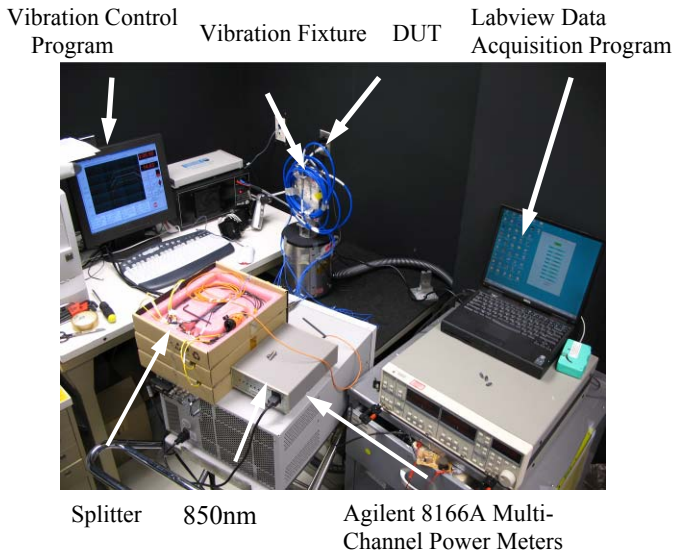


Figure 3: Random Vibration Testing Set up For the Laser Ranging Optical Fiber Assemblies

At the input an 850 nm LED was connected to a splitter so that it could be injected into the seven fiber array assembly set with one channel of the splitter connected to the detector. The optical source is monitored for power transients such that those variations can be subtracted from the end result test data. The reference fan out assemblies used here have on one side an array optical fiber connector and on the other side seven individual FC optical fiber connectors. These fan out assemblies that take individual channels and couple them into the array set (and vice versa) are used on the input and output sides of the set up. The individual channels are monitored with the HP8166 multi-channel optical power multi-meter and logged to a data file using LABVIEW software. Even though all channels were monitored the data is presented as an average for the bundle since no single channel cracked or increased insertion loss beyond acceptable limits.

For the insertion loss numbers in Table 3, note that all negative numbers represent a gain and positive numbers represent an increase in loss. It is also important to remember that although 850 nm is not the operational wavelength for the integrated system, this test was primarily a test of the interconnection between each interface and those of the reference assemblies as well, and therefore the wavelength was adequate for providing delta change results in the mechanical optical interface during vibration testing. When both assembly sets were tested at 532 nm they were removed from the in-situ set up and inserted into a different insertion loss measurement system. This accounts for the difference in measurement of the change in insertion loss at 850 nm and at 532 nm. All end faces were inspected after testing was complete to validate the integrity of the fiber end faces.

Table 3: Random Vibration Optical Insertion Loss Change (Δ IL) Test Results

Vibration Level	Axis Orientation	SET 1 Δ IL, 850 nm (dB)	SET 2 Δ IL, 850 nm (dB)	SET 1Δ IL, 532 nm (dB)	SET 2Δ IL, 532 nm (dB)
20grms	x-axis	0.026	0.097		
	y-axis	0.010	0.011		
	z-axis	0.036	-0.006		
14grms	x-axis	0.003	0.053		
	y-axis	0.003	-0.023		
	z-axis	0.039	-0.019		
10grms	x-axis	0.017	-0.020		
	y-axis	0.015	0.011		
	z-axis	0.000	0.016		
Post Test				0.37	0.11
Largest Loss ~ Δ		0.04	0.10		
Largest Loss ~ Δ in single channel		0.09	0.18		

The cable assemblies performed adequately during vibration testing and were then inserted into a thermal validation insertion loss experimental set up for requirements validation of the thermal levels expected for the Laser Ranging optical fiber assemblies.

2.4 Thermal Testing

Both LR engineering model sets were tested for the survival thermal requirements for the Laser Ranging assemblies. The test was conducted to validate that the cable assemblies as a set would function adequately during the life of the mission and during thermal exposure. Since this type of aging testing takes weeks, the ramp rate used is accelerated over the ramp rate used for thermal workmanship testing. The output power was once again monitored in-situ at both 850 nm and 532 nm. Due to the lack of sufficient resources to monitor all 14 channels with 532 nm, 850 nm was used on the channels not measured with 532 nm to detect if any cracking of the fiber was occurring during testing. After testing was complete the assemblies were again tested in an insertion loss measurement system at 532 nm and the end faces inspected for any potential damage.

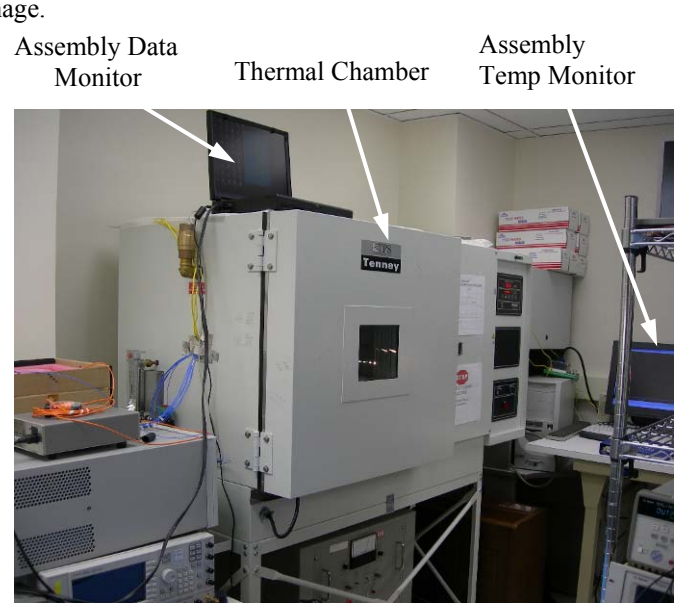


Figure 4: Thermal Cycling Testing Set-Up for the Laser Ranging Optical Fiber Bundle Array Assemblies

For this test, the thermal range was -55°C to +80°C, for 100 cycles, at 2°C/min and 30 minute dwells at the extremes. The reference fan out assemblies were used again to couple light in and out of the LR test sets. The interconnection of

both fan out arrays to the test sets were placed inside the thermal chamber so that all interfaces were exposed to the thermal extremes. Therefore, instead of open beams at either ends of the assemblies there were two connections to other array assemblies. This of course would potentially over estimate the losses over the thermal range. For registering the relative insertion losses at 850 nm the HP8166 was used and for registering the data at 532 nm the Newport 2930C and an HP8153 with a visible detection module were used. Again the source was monitored and that left three channels for monitoring thermal induced relative insertion loss. One of the outer channels was chosen for monitoring on each assembly set. On Set 1, channel 6 was monitored and on Set 2, channel 2 and 6. During testing the thermal data was captured to compare to the registered losses over temperature. As expect the losses rose as the temperature dropped. After the thermal cycling testing for 100 cycles was complete, one set was removed from the test set up and measured while the other was tested for an additional 10 cycles but this time using a profile of -70°C to +85°C, 2°C/min ramp rate and 30 min dwell at 85°C and 60 min dwell at -70°C.

The data is presented in Tables 4 through 9. The maximum relative change in optical transmittance is shown in Table 4 for Set 1 and in Table 5 for Set 2. Note that the change in transmittance included losses and gains over the thermal range. It was expected that the losses for 850 nm would be higher than for 532 nm since the fiber was not designed for the 850 nm wavelength. The data was used to simply monitor for fiber cracking over the 100 cycles.

Table 4: Set 1, Maximum Relative Transmission Change in dB over 100 thermal cycles, -55°C to +80°C

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5	Fiber #6	Fiber #7
WL @532nm						0.40	
WL @850nm	0.78	0.70	1.07	0.96	0.99		0.53

Table 5: Set 2, Maximum Relative Transmission Change in dB over 100 thermal cycles, -55°C to +80°C

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5	Fiber #6	Fiber #7
WL @532nm		0.40				0.50	
WL @850nm	1.27		0.62	0.82	0.64		1.06

The maximum transmission change at 532 nm was 0.5 dB for the three channels monitored. The other two channels both registered maximum transmission changes of 0.4 dB. The final relative insertion loss after the completion of the 100 cycle test, with the temperature ~ 25°C is presented in Tables 6 for Set 1 and in Table 7 for Set 2.

Table 6: Set 1, Relative Insertion Loss (dB) Registered after 100 Thermal Cycles Complete

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5	Fiber #6	Fiber #7
WL @532nm						0.03	
WL @850nm	0.06	-0.02	0.25	0.12	-0.05		0.007

Table 7: Set 2, Relative Insertion Loss Registered after 100 Thermal Cycles Complete

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5	Fiber #6	Fiber #7
WL @532nm		-0.22				-0.32	
WL @850nm	-0.78		-0.27	-0.49	-0.61		-0.59

In Tables 6 and 7 it shows low losses for Set 1 and small gains for the final relative insertion loss for Set 2. Therefore, both assembly sets completed the 100 cycle thermal testing to the survival limits without incident and once the temperature returned to room temperature, the losses registered either as equal or less than 0.03 dB at 532 nm.

Table 8: Set 2, Maximum Relative Transmission Change in dB over 10 thermal cycles, -70°C to +85°C

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5	Fiber #6	Fiber #7
WL @532nm		0.40				0.55	
WL @850nm	1.53		1.06	0.89	0.93		1.35

Once Set 1 was removed from the thermal chamber, Set 2 was tested for an additional 10 cycles and an extended thermal range. Even though the lower limit of the survival requirement is -55°C and the assemblies performed well, we were curious if the new 416 stainless steel ferrules would out perform the previously tested assemblies with 303 stainless steel ferrules.

Table 9: Set 2, Relative Insertion Loss Registered (dB) After the additional 10 Thermal Cycles Completed.

	Fiber #1	Fiber #2	Fiber #3	Fiber #4	Fiber #5	Fiber #6	Fiber #7
WL @532nm		-0.10				-0.07	
WL @850nm	-0.12		-0.07	-0.16	-0.22		-0.15

In tests performed last year, with assemblies fabricated with 303 stainless steel, the fibers cracked when the thermal range was reduced below -60°C. This additional test of 10 cycles was validation that indeed the change in materials alleviated the risk down to -70°C. At 532 nm the transmission change is slightly larger than when the thermal range was narrower by 20 degrees. This was expected.

Table 9 shows the final data for cable Set 2 after the additional 10 thermal cycles were complete. There were no cracked fibers as identified by this data. All end faces remained undamaged after testing was complete per visual inspection. The data shows slight gains per channel at both wavelengths. The slight gains registered post a thermal cycling test has been seen when testing array MTP connectors during years previous.[5,6] After the thermal testing was completed each assembly was tested in the standard laser ranging insertion loss measurement system at 532 nm. Set 2 measured 2.85 dB and was 2.81 dB after vibration and prior to thermal testing, which is a difference of 0.04 dB change for thermal testing. Set 1 was examined prior to testing in the IL measurement system and was caused to crack during measurement of how far the outer most bundle jacket had shrunk back. The jacket had shrunk nearly 2 cm and left the inner cables vulnerable to handling related failures. The fibers now lacking proper strain relief were easily cracked when the cable was bent just behind the connector during examination. The final measurement for thermal on Set 1 at 532 nm showed that the handling related crack increased the bundle insertion loss by 0.85 dB.

2.5 Radiation Testing

The gamma radiation test was performed on three samples at NASA GSFC's Cobalt 60 Radiation Facility in Code 561. Two cable samples were exposed at room temperature at different dose rates (low and high) and one at cold temperature at the low dose rate. Table 10 shows the three conditions.

Table 10: Radiation Induced Insertion Loss Test Conditions for Three 9.5 meter Samples

Condition for Radiation Testing	Dose Rate	Temperature	Total Dose
Condition 1	152 rads/min	24°C	1.1 Mrad
Condition 2	18.2 rads/min	24°C	130 Krad
Condition 3	18.2 rads/min	-50°C	130 Krad

Three flexlite cable (not in the seven fiber bundle) spools of 9.5 meters each were put into the testing set up such that only the spools would be exposed and the lead in and lead out cables would not. The radiation dose was monitored as was the optical fiber transmission through each of the fibers under test. Data was logged once per minute and the source was also monitored once per minute. The power level was reduced to below 1 microwatt per channel at the input to the fiber under test at 532 nm. The same Newport detectors and HP power meter were used to monitor the fibers and the source. All measurements were compared to the fiber transmission just prior to the radiation exposure began. Once the testing was completed, all the data was analyzed to provide an extrapolation model. In previous publications that included radiation data, we presented an enhanced version of the Friebele model for usage over various temperatures. The extrapolation equation takes the form of

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

where 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.[6]. Based upon the model equation (1) no general model can be derived without making some assumptions about the constants C_0 and f. Two sets of data are necessary to determine which C_0 and f are approximate to use the equation 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 generated using all three data sets. Solving for f(T) using the two data sets of condition 2 and condition 3 (two different temperatures using the same dose rate) the expression is

$$f(T) = -2.7027 * 10^{-4}T + 0.6565 \qquad (2)$$

Solving for $C_0(\phi)$ using two data sets of high and low dose rate tests on Figures 1 and 3, the expression is

$$C_0(\phi) = -7.27 * 10^{-7}\phi + 1.4887 * 10^{-4} \qquad (3)$$

In equation (3), as the dose rate becomes very small or less than 1 rad/min which is typical of space flight background radiation, C_0 becomes $1.4887*10^{-4}$, 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 (dB) at room temperature of 24°C can be extrapolated with:

$$A(D) = 1.4887 * 10^{-4} \phi^{0.35} D^{0.65} \quad (4)$$

To scale the units to dB/m, A(D)/L with L equal to 9.5 m which is the actual length of the cables under test, Figure 5 shows the extrapolation curve given a dose rate of 1 rad/min, up to a total dose of 200 Krads for room temperature of 24°C and for -50°C.

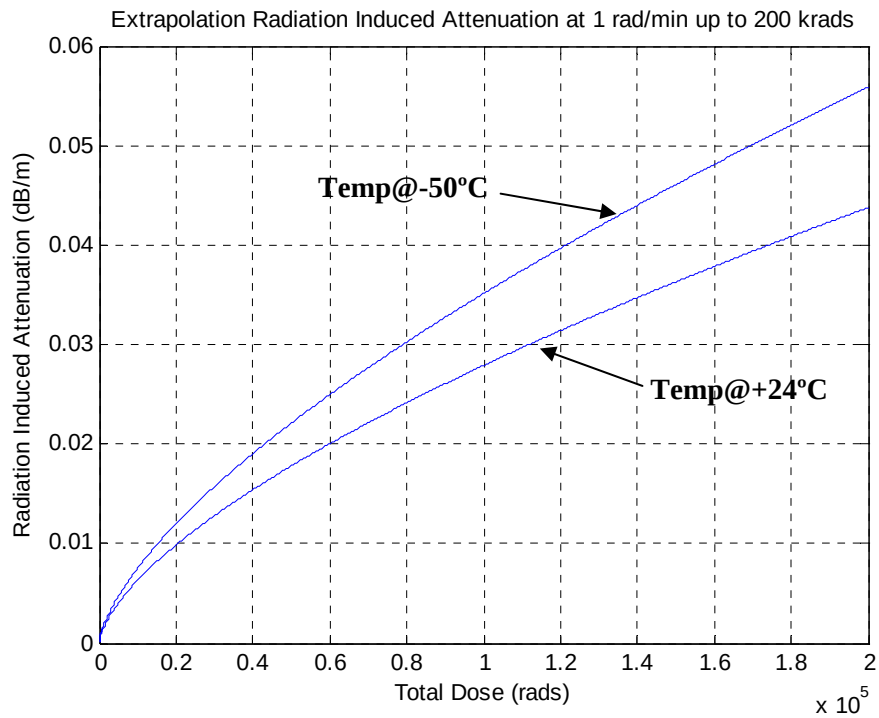


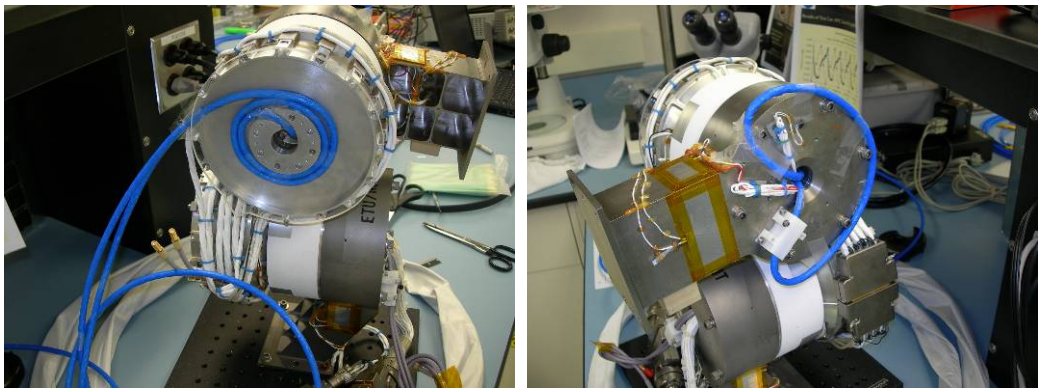
Figure 5: Extrapolation Curve at the dose rate of 1 rad/min up to 200 Krads at temperature of 24˚C & -50˚C

To compare the difference that lowering the temperature makes to the extrapolation results, if we use -50˚C to calculate the radiation induced attenuation at 200 Krads, the result is 0.056 dB/m. For the same conditions using the graph in Figure 5 the radiation induced loss at 200 Krads and 24°C is slightly lower at 0.044 dB/m as can be seen in Figure 5. This extrapolation model allowed us to set realistic allocations for the radiation induced loss over a range of worst case cold temperatures and shielding conditions across the LRO space craft. The bundle materials that surround the flexlite cable in the actual application do provide some shielding but does not significantly affect the radiation induced attention.

2.6 Gimbal Motion Test

One of the earliest concerns for the LR mission was if the optical fiber bundle could survive being flexed in the set of gimbals while being at a cold temperature. The first test summarized in reference 7 was conducted with a single strand of flexlite cable not in the 7 fiber bundle. When the new bundle arrived with the 3 inch twist it was terminated to individual FC optical fiber connectors at each end and was inserted into the gimbal and routed so that it would be included into two cable wraps to simulate the routing of the cable through a two gimbal system. Due to the size of the gimbals, using this method was the only way to fit the gimbal system into a thermal chamber such that it could be maintained at a temperature of -20°C and -10°C while in motion. The objectives for this test were to 1) ensure that the cable would not break during the life of the mission and 2) to identify the expected changes transmission during the flexing of the gimbals at cold temperature where we expected the largest amount of loss to occur. Therefore the test was

conducted in-situ at 850 nm and 532 nm. Testing on the bench outside of the thermal chamber and inside the thermal chamber at cold temperatures showed no difference between the change in transmittance for the 7 fiber bundle. Therefore most of the channels were monitored at 850 nm with measurements at 532 nm made weekly on all channels.
The mission requirement for the gimbal motion was approximately 5500 mechanical cycles, in which going from the zero position to the position at 180° and back constituted a complete cycle. The gimbal cycling test at cold temperature was conducted for nearly 17,000 mechanical cycles without incident. In addition the gimbal system with the fiber bundle endured another 2000 cycles at room temperature. The optical transmittance change was higher than expected for the bundle but the bundle with the 3 inch twist was under a great deal of stress due to the design as demonstrated by the un bent insertion loss of the optical fiber at 532 nm. The test will be repeated with the 18 inch twist bundle in the next few months and will be published at a later time. The pictures in Figure 6 a and b show the front of the gimbal with cable in the cable wrap and the back view of the gimbal where the cable was looped to go back down the shaft to be wrapped into another cable wrap. Where Figure 6 a shows the gimbal in the tight position or position at zero degrees, Figure 7 a shows the gimbal in the loose position or at position 180 degrees.



Figures 6 a) front view of the cable inside of gimbal in tight configuration, b) back view of gimbal.

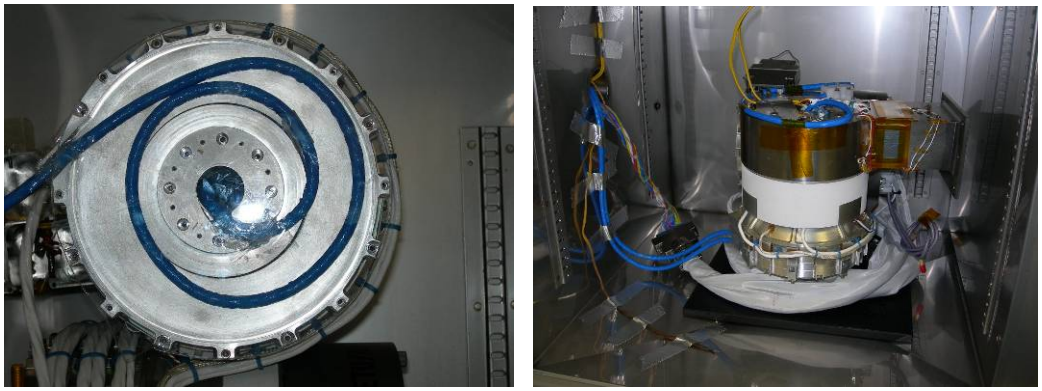


Figure 7a) Gimbal in loose position, b)Inside the Thermal Chamber, Gimbal with Fiber Bundle Integrated.

The bundle was monitored through out the gimbal motion cold test and in Table 11 the parameters of the lifetest are listed. Since both cable wraps were fitted in the tight position, both gimbals were tight at zero degrees position and both were loose at 180 degrees gimbal position. This showed the worst case scenario for the optical fiber relative insertion loss with both cable wraps tight and loose at the same time.

Table 11: Parameters of the Mechanical Gimbal Life Testing at Cold Temperatures.

Temperature	Wavelength	Mechanical Gimbal Cycles
-20°C	532 nm	223
-20°C	850 nm	6301
-10°C	850 nm	10497

The reason the test was limited to -20°C was due to the gimbals themselves by specification being limited to exposures equal to or greater than -20°C. The gimbals used for this application were engineering units that were built for the Tropical Rainfall Measuring Mission project years previous. The fiber performed similarly throughout the entire test. The data had to be broken down into subsets for analysis during testing. Two examples of the gimbal data "snapshots" are in Figures 8 and 9 and in both cases the change in insertion loss is determined by the absolute value of the full IL excursion. For example during the beginning of the test at 532 nm transmission the full excursion was 0.60 dB for change in insertion loss during -20C cold temperature exposure over a complete gimbal motion cycle (Figure 7). During testing at 850 nm the full excursion was ~0.50 dB during the last six cycles of the testing (Figure 10). So under the worst case conditions it was expected that if both gimbals were tight at the same time, than the losses would increase by no more than ~ 0.60 dB using the 3 inch twist bundle. At no time during testing did any of the fiber channels stop transmitting due to breaks or cracks. Post cycling testing actually showed reduction in the bundle insertion loss at room temperature when compared to the insertion loss prior to cold temperature and 19,000 gimbal cycles of testing. During testing 532 nm test data was registered on the bundle once per week on the bundle losses increased slowly over the several months of testing but did not register once the system returned to room temperature and compared to the pre testing insertion loss in the gimbal.

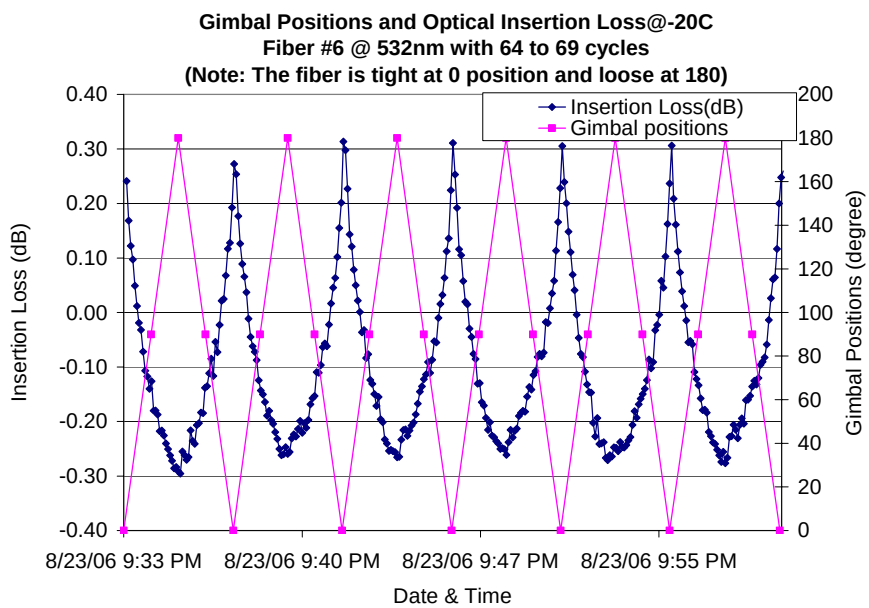


Figure 8: Beginning of Lifetest; - Data "Snap-shot" of Optical In-situ Data During Six Gimbal Motion Cycles at -20°C

In comparing Figure 9 and 10, the gimbal motion induced losses increased by ~ 0.10 dB when the temperature decreases from -10°C to -20°C at 850 nm. By comparing the data in Figure 8 and Figure 9, the gimbal induced insertion loss became only slightly larger at 532 nm by ~ 0.05 dB as compared to the data taken at 850 nm. We expect the 18 inch twist bundle to perform with a reduction in the gimbal induced insertion loss when that test is conducted later this year since the twist is less stressful to the fiber in the 18 inch bundle as opposed to the 3 inch bundle.. The conclusion of this testing was increased confidence that the cable would survive under cold gimbal motion and within an allocation that could be captured in the system level analysis for expected losses over the time of the mission.

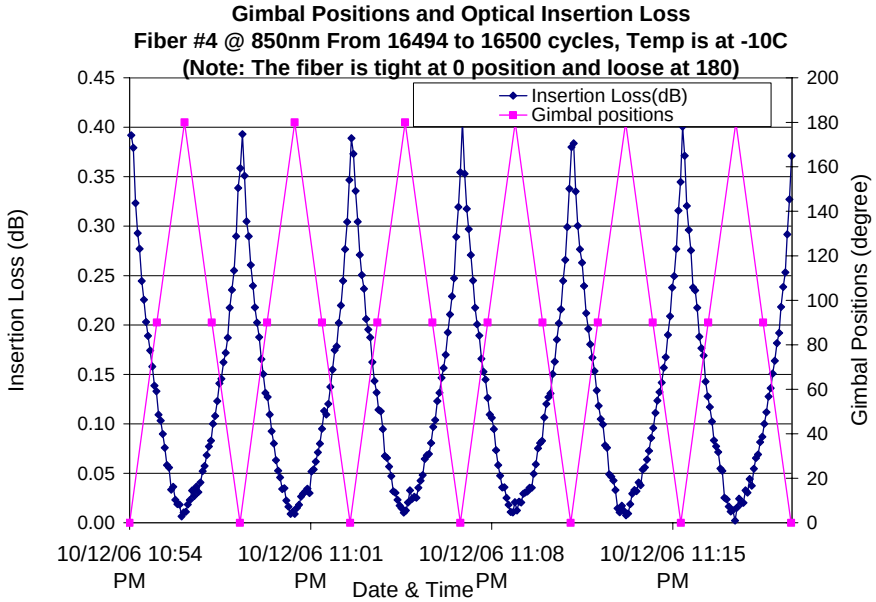


Figure 9: Near End of Lifetest - Data "Snap-shot" of Optical In-situ Data During Six Gimbal Motion Cycles at -10°C

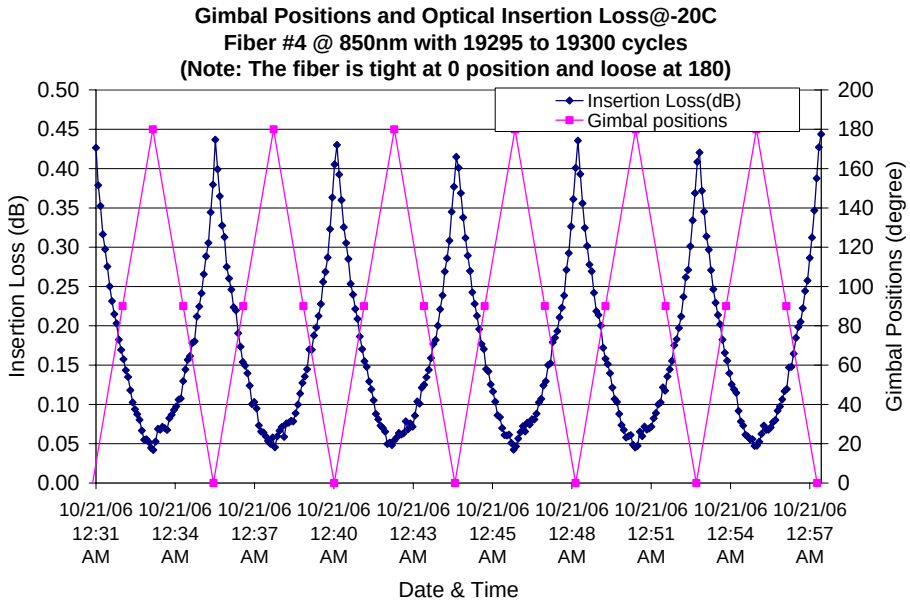


Figure 10: End of Lifetest - Data "Snap-shot" of Optical In-situ Data During Last Six Gimbal Motion Cycles at -20°C

CONCLUSION

Presented here were some of the results of the engineering model requirements validation testing for the optical fiber array bundle assemblies for the Laser Ranging mission on the LRO. Small design changes have been made to the manufacturing of the bundle assemblies as a result of this testing and will are incorporated into the flight design. Additional flight like engineering models will be tested again later this year under the same conditions described here with the exception of the radiation test. Although small variations to the manufacturing procedure have been made since this testing was conducted to alleviate handling related failures, these results validated the mission performance requirements during worst-case scenario environmental exposure.

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