

# Space Flight LiDARs, Navigation & Science Instrument Implementations: Lasers, Optoelectronics, Integrated Photonics, Fiber Optic Subsystems and Components

Melanie N. Ott\*<sup>a</sup>, Cameron H. Parvini<sup>a</sup>, Hali L. Jakeman<sup>a</sup>, W. Joe Thomes<sup>a</sup>, Eleanya E. Onuma<sup>a</sup>

<sup>a</sup>NASA Goddard Space Flight Center, 8800 Greenbelt Drive, Greenbelt, MD, USA 20771-2400

## ABSTRACT

For the past 25 years, the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center's Photonics Group in the Engineering Directorate has been substantially contributing to the flight design, development, production, testing and integration of many science and navigational instruments. The Moon to Mars initiative will rely heavily upon utilizing commercial technologies for instrumentation with aggressive schedule deadlines. The group has an extensive background in screening, qualifying, development and integration of commercial components for spaceflight applications. By remaining adaptable and employing a rigorous approach to component and instrument development, they have forged and fostered relationships with industry partners. They have been willing to communicate lessons learned in packaging, part construction, materials selection, testing, and other facets of the design and production process critical to implementation for high-reliability systems. As a result, this successful collaboration with industry vendors and component suppliers has enabled a history of mission success from the Moon to Mars (and beyond) while balancing cost, schedule, and risk postures. In cases where no commercial components exist, the group works closely with other teams at Goddard Space Flight Center and other NASA field centers to fabricate and produce flight hardware for science, remote sensing, and navigation applications. Summarized here is the last ten years of instrumentation development lessons learned and data collected from the subsystems down to the optoelectronic component level.

**Keywords:** Spaceflight, LiDAR, Lasers, Optoelectronics, Integrated Photonics, Photonic Integrated Circuits, PICs, Fiber Optics, Detectors, InP, Radiation, Environmental, Screening, Qualification, Gateway, Europa, Mars, Moon, Optics, James Webb Space Telescope, Europa Clipper, Navigation.

## 1. INTRODUCTION

NASA has announced the Moon to Mars initiative with emphasis on a Moon orbiting "Gateway" as a docking, refueling and supply station from which many smaller scope instruments, habitats and vehicles can be housed<sup>1</sup>. To meet the aggressive schedule, the Gateway will have to rely on commercial systems and components that can sustain sufficient performance in the space environment. Over the past decade, instrument schedules have also become more aggressive and have therefore necessitated a knowledge based risk mitigation approach towards the usage of commercial technologies. Effectively fabricating technology for use on the Gateway will require the application of relevant heritage expertise (lessons learned) collected from multiple instrument programs. Generating custom optical, optoelectronic, and photonic hardware solutions, required for building reliable laser ranging and detection (LiDAR), science and navigation instruments, necessitates a complete understanding of failure mode anomalies for the subsystems, components and parts. Utilizing failure mode knowledge from previous space missions is therefore critical to successful design and implementation of reliable systems without increased schedule and cost risk. NASA Goddard Space Flight Center (GSFC) has been providing custom LiDAR, science, and navigation instrumentation for more than 20 years<sup>2</sup>. Throughout this time, Goddard has worked in collaboration with contractor partners to apply risk mitigation strategies when implementing commercial technology since most all photonics components are commercial and not standardized from a strict EEE parts perspective. The NASA GSFC Photonics Group specializes in risk mitigation strategies when building instrumentation with commercial optoelectronic, photonic and fiber optic components. They possess a thorough knowledge of packaging and device failure modes. This knowledge, repeatedly demonstrated, has led to multiple mission successes. In addition, the Photonics Group's diverse skillset has enabled them to be adept at providing unique solutions under strict budgets and schedule restraints. An overview from the past ten years of production, application, screening and qualification is presented in this paper from multiple LiDAR, science and navigation space flight applications.

## 1.1 Background

During the past 20 years, NASA GSFC has produced multiple LiDARs that were transported to remote locations including Mercury and the Moon. During the Mercury journey, the Mercury Laser Altimeter (MLA) instrument was facing Earth. Using the GSFC Satellite Laser Ranging Station and MLA, pulsed signals were exchanged, establishing the longest laser link in space, across distance of 24 million kilometers<sup>3</sup>. The two-way laser link was not part of the original requirements. This experiment illustrated the adaptability of NASA GSFC's core competency in remote sensing and communications. This versatility was again demonstrated seven years later, with the Lunar Reconnaissance Orbiter (LRO) using the Laser Ranging telescope/optical fiber link on the High Gain Antenna, to communicate with Lunar Orbiter Laser Altimeter (LOLA). The GSFC laser ground station successfully transmitted images to LOLA while simultaneously ranging. The communication demonstration over 0.39 million kilometers to LOLA, was not an original mission requirement but it proved the feasibility of laser communications to the Moon<sup>4</sup>. Both the two-way laser link with MLA, and the LOLA communications experiment on LRO, used flight optical fiber assemblies and arrays, fabricated and implemented by the Photonics Group<sup>5,6</sup>. The Photonics Group worked closely with the Jet Propulsion Lab, to develop and produce the flight fiber optic assemblies for the Curiosity Rover, Mars Science Lab (MSL) Chemistry & Camera (ChemCam) instrument and the Mars2020 Rover, "SuperCam" instrument currently in integration<sup>7</sup>.

Moving forward to the vision of Gateway, there are several enabling technologies being developed as navigational instruments for landing on the Moon and Mars. These technologies benefit from the last 20 years of remote sensing instrumentation lessons learned. Two instruments funded by the NASA Space Technology Mission Directorate, Safe and Precise Landing – Integrated Capabilities Evolution (SPLICE) program for landing applications are: 1) The Navigational Doppler LiDAR team, developed at NASA Langley Research Center under Principal Investigator Farzin Amzajerdian, working in collaboration with the Photonics Group for component radiation testing, and 2) The Hazard Detection LiDAR, a GSFC in-house design currently in development with commercial components at the NASA GSFC facilities<sup>8,9</sup>.

Another enabling navigational instrument that the Photonics Group supports at GSFC is "Kodiak", formerly named the Goddard Reconfigurable Solid-state Scanning Lidar (GRSSLi). This real-time 3D imaging LiDAR will provide autonomous docking navigation for the "Restore-L" Satellite Servicing Mission to replenish the fuel on Land Satellite, "Landsat-7"<sup>10</sup>. To build this instrument, the Photonics Group is providing component selection, along with subsystem packaging and qualification services.

## 2. DEVELOPMENT OF LASER SUBSYSTEM COMPONENTS: EARTH ORBITING LASER DETECTION AND RANGING

Two earth observing Laser Detection and Ranging (LiDAR) instruments, significant to understanding climate change were launched in 2018. The Ice, Cloud and Land Elevation Satellite – 2 (ICESat-2) mission, Advanced Topographic Laser Altimeter System (ATLAS) instrument was launched in September 2018<sup>11</sup>. The Global Ecosystem Dynamics Investigation (GEDI) mission instrument was launched in December 2018<sup>12</sup>. The objective of ATLAS is to study the "cryosphere" in its orbit on the ICESat-2 spacecraft built by Northrup Grumman (formerly Orbital Alliant Techsystems Inc.). The GEDI instrument is monitoring Earth's forest and land topography from its location on the International Space Station. The ATLAS laser was produced by FiberTek. However, the GEDI laser was a NASA GSFC in-house build, tailored to meet the science requirements based upon previous designs of the High Output Maximum Efficiency Resonator (HOMER) class laser system<sup>13</sup>. An overview of significant lessons learned, regarding screening and testing of laser components from these LiDAR missions is discussed in Sections 2.1 & 2.2.

### 2.1 ATLAS Laser Subsystem for ICESAT-2

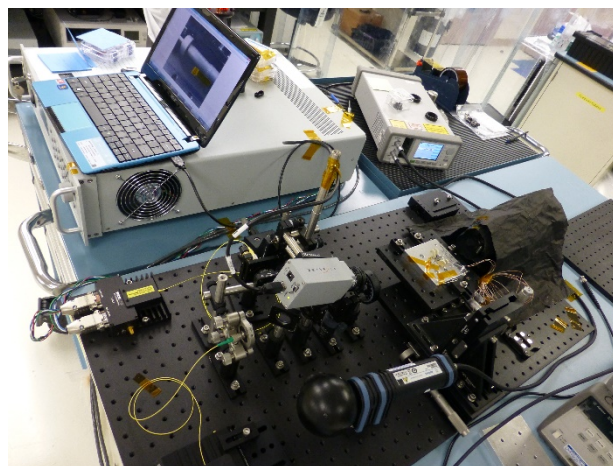
The ATLAS instrument took approximately 9 years to develop, integrate and test at NASA GSFC. It was an ambitious endeavor with a sophisticated on-board calibration system for keeping a precise lock on the reflected photons from ice sheets and forest canopies. The ATLAS instrument has surpassed the expected data resolution and is currently measuring sea ice depth to within an inch. To achieve this, the ATLAS instrument laser system generates a short pulse width (< 2 ns) at 10 kHz and achieves this with a Q-switch device<sup>14</sup>. The lifetime number of shots expected for the laser is 1000 times higher than previous LiDAR missions<sup>15</sup>.

During the initial part inspection, screening, and engineering unit builds, several Q-switch crystals exhibited a bond failure. During development of the lasers, approximately 20% of the Q-switches exhibited signs of this bond failure at the time it was identified by FiberTek. An exploratory study was undertaken while production continued in order to determine the root cause while simultaneously avoiding significant schedule delays. The results of the study showed that a lack of rigorous documentation for the bonding process, workmanship screening and workmanship cleanliness directly led to the observed delamination. In addition, there was a clear need for component-level screening tests and verification since all of the components in the laser system were constructed from commercial parts—as is true of many laser and optoelectronic systems fabricated for NASA space instruments. The combination of aggressive schedules and commercial component implementation increases the failure risk. With complicated systems such as lasers, which in turn utilize an increasing number of commercial off the shelf (COTS) subcomponents, the number of potential failure modes quickly becomes expansive. When the situation is further complicated by an aggressive schedule, some processes to ensure a highly reliable space flight system are inevitably skipped for schedule reasons. Although the program schedule did require the flight builds to continue in parallel with the delamination study, the engineering model build *did* enable ATLAS engineers to find the issue in a test unit. This allowed for screening tests to be developed, and plans for corrective actions to avert the failure for future flight builds.

In order to acquire a quantitatively significant screening result before and after an environmental verification test, an extremely stable experimental setup was required and Photonics Group assembled it. A test plan consisting of 1) a random vibration test, 2) thermal cycling to accommodate both testing and operation plus margin and 3) an accelerated life test was conducted in the Group cleanroom facilities.



**Figure 1:** ATLAS Q-Switch vibration test in GSFC Photonics Group environmental test lab.



**Figure 2:** ATLAS Q-Switch optical contrast ratio measurement in the Photonics optoelectronic testing lab.

Before and after each applied environmental stress, a steady and repeatable contrast ratio test was conducted to evaluate the Q-switch devices. A change in contrast ratio performance would show a change of position of the crystal with respect to its mount.

## 2.2 The Light Emitting Diode for the On-Board Calibration Systems

Included on the ATLAS optical bench was the Telescope Alignment Monitoring System (TAMS) light source. This subsystem was critical to the on-board calibration system. It provided a reference point for the pointing direction of the Receiver Telescope while it attempted to maintain view of the reference ground track, and additionally assisted the spacecraft attitude control system in keeping the observatory pointed in the proper direction. The operating principle of TAMS was dependent upon two Light Emitting Diode (LED) sources that were collimated, filtered, and free-space coupled into a fiber array to fan out assembly, before being transmitted to the Aft Optics Focal Plane. The Photonics Group performed screening, radiation, and subsequent thermal qualification testing of the TAMS LED sources, ensuring

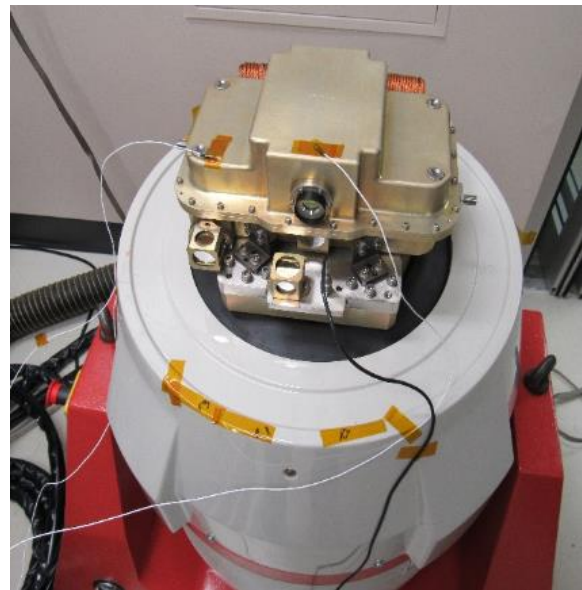
that the components were capable of supplying stable optical output throughout the lifetime of ICESAT-2. The TAMS array assemblies were produced and integrated by the Photonics Group.

### 2.3 Global Ecosystem Dynamics Investigation LiDAR System (GEDI)

The GEDI mission utilized a Beam Dithering Unit (BDU) to acquire more ground tracks without employing internal moving mechanical parts. The BDU is an electro-optical beam steering unit that alters the pointing of the laser beam. The lack of internal mechanical steering results in a highly reliable subsystem with very stable output beams. For the GEDI mission, each laser has a corresponding BDU mounted at its output. The BDU features a sealed and pressurized enclosure with all the necessary optical components and an electrical driver board inside which includes a set of Q-switches. Contrary to the ATLAS Q-switch of a crystal bonded to a mount, the GEDI BDU Q-switch is a crystal packaged into a sealed and inaccessible housing.



**Figure 3:** Joe Thomes at the BDU fabrication bench during the flight builds.



**Figure 4:** The beam dithering unit on the shaker during vibration qualification testing.

Due to a change in both vendor and component from ATLAS to the GEDI BDU and a system design that required matched pairs of Q-switches, initial inspections of the COTS components revealed optical inconsistencies that were traced to a series of workmanship issues. First, was the location of the mounted crystal inside of its packaging, and second, was the amount of bonding material used in the packaging. In commercial applications these devices are considered very reliable. However, in a high performance, high reliability, space flight application that requires precision of matched sets, these construction issues drove the development schedule and required crafting another tailored set of screening tests to evaluate the failure potential. Due to the difference in packaging configuration from ATLAS, the BDU Q-switch screening tests required construction analysis methods for internally interrogating the devices prior to pursuing acceptance performance testing.

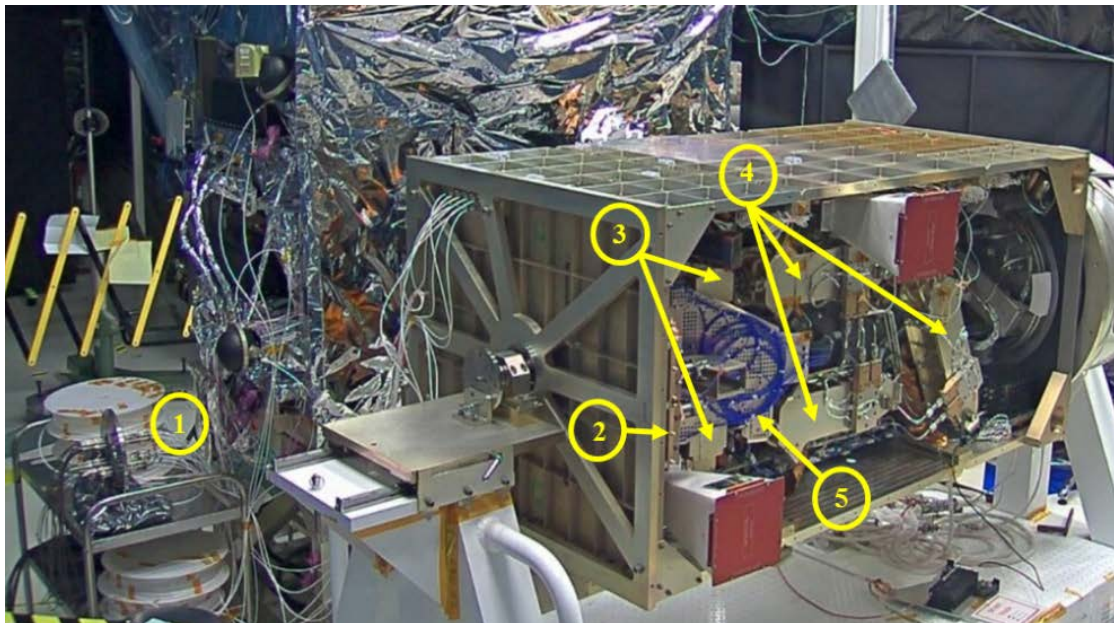
In addition to the BDU flight hardware, the Photonics Group supplied several subsystem and component level equipment, screens and tests for the GEDI instrument. Table 1 summarizes these activities. The items identified in column 1 of Table 1, correspond to the arrow diagrams numbers in Figure 5. The team was responsible for building the bench checkout equipment fiber optic test rack (item #1 from Table 1 and Figure 5) from commercial components. This test rack accepted start pulse input and simulated scenes back to the instrument to test its full functionality. This rack was used through-out flight qualification level environmental testing to evaluate the instrument performance. The GEDI detectors (item #2 in Table 1 & Figure 5) were qualified using the vibration shaker system seen in Figure 4, and a nearby thermal vacuum chamber, in the same lab. The detector thermal vacuum testing had to be monitored 24 hours/day for several weeks while the detectors were undergoing proto-flight qualification. Six flight and two spare detector modules

were required for instrument delivery. For expediency, the detector modules were tested as they were available post in-house (GSFC) production. The modules were tested in groups of four at a time, during thermal vacuum proto-flight testing. The laser components (item #4 of Table 1 & Figure 5) were inspected and screened prior to delivery to the laser fabrication team. The laser fiber optic feedthrough was designed, developed and integrated by the Photonics Group into all of the flight laser systems. The multiple flight fiber optic assemblies for the receiver detectors and the laser were developed, produced and integrated by the Photonics Group. These assemblies included a triple fiber array to fan out assembly for the laser start pulse detection at the detector modules and the bench check-out equipment.

**Table 1:** Summary of space flight subsystem screening, qualification and hardware deliveries to GEDI.

#	GEDI Subsystem	Hardware Deliveries
1	Checkout Equipment	Development, fabrication & integration: laser & detector test rack used for qualification of flight instrument, TVAC fiber assemblies down to -120°C.
2	Detector Qualification	Qualification of engineering & flight unit detectors
3	Laser Beam Dithering Unit	Development, fabrication, qualification & integration of engineering and flight units
4	Optical Laser Components	Development, qualification & fabrication of flight laser fiber optic feedthrough. Incoming inspection of laser components.
5	Flight Fiber Optic System	Development, qualification & integration of flight 600/660 μm fiber optics transmission >97%; 200/220 μm triple fiber arrays for start pulse. Adapter inspections and screening.

The GEDI deliverables from the Photonics Group to the instrument team, listed by item number in Table 1, correspond to the identifying numbers in Figure 5 below.



**Figure 5:** The Global Ecosystem Dynamics Investigation (GEDI) Flight Instrument System.

### 3. OPTOELECTRONICS COMPONENT SCREENING AND QUALIFICATION TESTING

For more than a decade, the Code 562 Photonics Group has performed optoelectronics screening and qualification testing for a variety of NASA program instruments and the instruments for private industry partners. These experiences have been leveraged to design intelligent, cost-effective approaches that isolate and characterize failure modes for modern spaceflight components. Within the field of optoelectronics, the technology has advanced rapidly and created a desire for more compact packaging—a fact that will increasingly complicate the associated test requirements. Despite the perceived difficulty, screening and qualification testing is fundamental to providing sufficient confidence in the performance of these new components under space flight environmental conditions. Table 2 provides a brief summary of the Photonics Group optoelectronics parts analysis and testing undertaken during the last ten years, including milestone efforts for; the James Webb Space Telescope (JWST), Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-Rex), and the Restore-L Satellite Servicing Mission. These applications are discussed in the following sections.

**Table 2:** Code 562 Photonics Group Optoelectronics Mission Highlights (Decade 2009-2019).

Project	Part Type	Wavelength (nm)	Quantity	Dates	Screening	Qualification	Radiation	Packaging Analysis
SAA Harris	Laser Diode	635, 660	30	2009	x	x		x
JWST	LED	633	6	2009		x		
TSIS/GLORY	Photodiode	140 – 1100	25	2010	x			x
LADEE/MAVEN	LED	450 – 650	50	2010	x	x		
SSCP	LED	450 – 650	290	2012	x	x		x
GOES-R	LED	315	4	2012				x
ATLAS	Photodiode	400 – 1100	10	2013	x			
OTES	Photodiode	450 – 1050	60	2014	x	x		x
OTES	Pyroelectric Detector	4000 – 50000	24	2014	x	x		x
SSCP	LED	635	842	2010-2013	x	x	x	x
ATLAS	LED	520	300	2012 - 2013	x	x	x	x
Solar Orbiter	Laser Diode	850	70	2013 - 2014	x	x		x
Solar Orbiter	Photodiode	450 – 1050	70	2013 - 2014	x	x		x
OTES	Laser Diode	850	50	2014 - 2015	x	x		x
MOMA	Micropirani	N/A	25	2014 - 2015	x	x		x
SSCO	LED	450 – 650	1000	2016-2019	x	x	x	x
SAA ASU	Laser Diode	850	45	2017 - 2018	x	x		x
SAA ASU	Pyroelectric Detector	4000 – 50000	43	2017 - 2019	x	x		x
NASA GCD Program	Photonic Integrated	1550	8	2018 - Present	x	x	x	x

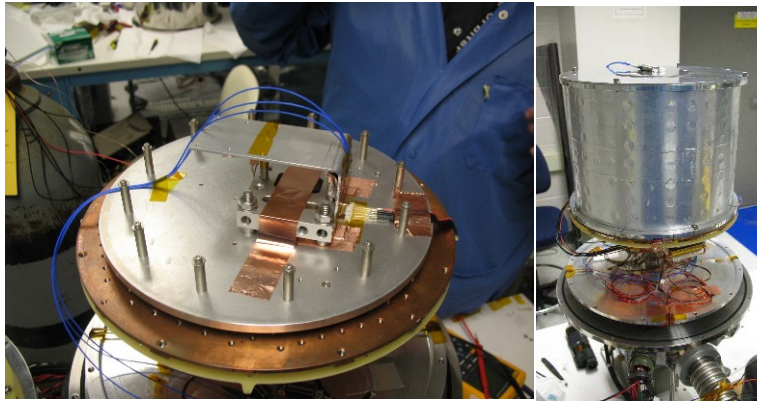
It is important to note that Table 2 does not include the qualification of various communications transceivers that have spanned the last three decades. Specifically, The Cloud-Aerosol Transport System (*CATS*), launched in January of 2015 contained the Micropac optical fiber transceiver that is now functional and aboard the International Space Station.

Anecdotal evidence indicates that the quantity of parts tested generally correlates with the risk posture associated with a project and application. System engineers tacitly accept a trade-off in risk when dedicating optoelectronics parts in small quantities for testing, as more complete statistical sampling requires groups in the many tens to hundreds. There are obvious barriers to testing optoelectronics in such quantities, not the least of which are high unit costs that further depend upon on the level of customization required by the program. Exceptions have been made in such cases at the expense of more extensive planning around evaluation activities. Again, screening and qualification can be effectively

performed with failure-mode-driven test campaigns, while using targeted experiments and parameters derived from the device configuration. Approaches of this kind exhibit the benefits of minimal cost, in addition to preventing the over-testing and thus erroneous elimination of otherwise suitable components. The following case studies illuminate work performed by the Photonics Group that underscore the expertise necessary to balance cost, risk, and schedule during optoelectronics screening and qualification.

### 3.1 James Webb Space Telescope (JWST) Cryogenic LED Qualification

In 2009, the James Webb Space Telescope Optics team approached the Photonics Group for assistance with qualifying surface mount LEDs for use in cryogenic temperatures. The light source channels were free-space coupled into fiber optic cables produced by the Photonics Group, enabling in-situ optical power measurements of the LED as a function of temperature, in addition to standard current and voltage (IV) characteristics. Figure 6 shows the test setup pre- and post-shroud installation.

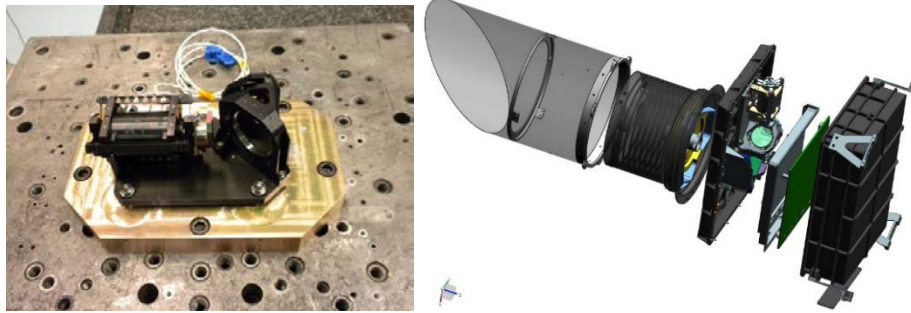


**Figure 6:** Cryogenic Test Setup for Surface Mount LED on JWST.

Due to both the component application and complexity associated with an in-situ cryogenic measurement, a relatively small quantity of parts were tested to meet confidence requirements in a limited timeframe. By understanding the failure modes associated with both the surface mount packaging and die, the Photonics Group was able to design an effective evaluation of the LED's flight performance.

### 3.2 Pyroelectric Detectors, Photodiodes, and Laser Diodes for the OTES Instrument on OSIRIS-REx

The Origins, Spectral Interpretation, Resource Identification, Security - Regolith Explorer (OSIRIS-REx) spacecraft is a six-payload mission that was launched in September of 2016 to the asteroid Bennu and arrived at Bennu on December 3 2018. The primary objective of the mission is acquiring and returning a sample of the asteroid to Earth, while a majority of the subsystems perform various remote sensing operations on the physical composition of the asteroid. One of the six payloads is the OSIRIS-REx Thermal Emission Spectrometer (OTES)—a point spectrometer that was developed at the Arizona State University School of Earth and Space Exploration. Though the OTES instrument is a Fourier Transform Interferometer with heritage from the Mars Global Surveyor and Mars Exploration Rovers, optoelectronic components within the instrument, required more specific characterization to ensure consistent in-situ operation. Figure 7 displays renderings of the OTES instrument and photographs of the Moving Mirror Assembly<sup>16</sup>.

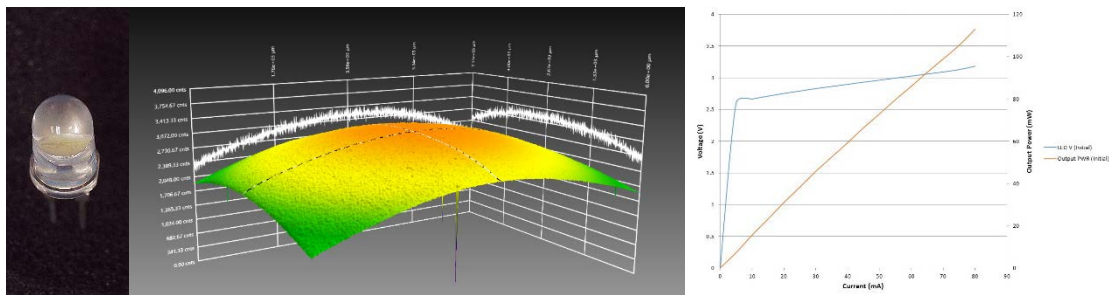


**Figure 7:** Moving Mirror Assembly Photo and OTES Rendering Reproduced from reference<sup>16</sup>.

Three types of TO-can (transistor outline type package) optoelectronic devices were supplied to the Photonics Group for screening and qualification activities: pyroelectric detectors, laser diodes, and photodiodes. Each part required a unique approach to efficiently qualify them for use in OTES, due in part to varied component costs that required lower quantities to meet program budget requirements. An extensive screening and qualification campaign was performed for each component to evaluate their long-term function and degradation modes ahead of flight. This involved frequent communication with Arizona State University (ASU) engineers to determine key performance parameters, mission requirements, and information furnished by the component manufacturers. In December 2018, several OSIRIS-REx subsystems including OTES were able to successfully “...reveal the presence of molecules that contain oxygen and hydrogen atoms bonded together...meaning that at some point, Benu’s rocky material interacted with water”<sup>17</sup>. The Photonics Group also partnered with ASU through a Space Act Agreement to perform similar component testing for a different space application.

### 3.3 White LED Qualification for the Restore-L Satellite Servicing Mission

The Restore-L spacecraft will be a satellite servicing platform that can rendezvous, redirect, and refuel other spacecraft in orbit, with the goal of enabling missions to operate beyond their designed lifetimes. The Restore-L team required support from the Photonics Group to screen and qualify encapsulated white Light Emitting Diodes (LEDs) for the Vision Sensor Subsystem (VSS) equipment used to illuminate targets for docking, arm maneuvering, tool navigation, and other servicing tasks<sup>18</sup>. Figure 8 reproduces a typical set of optoelectronic characterization data required for this endeavor.



**Figure 8:** Typical Encapsulated LED Characterization Data

The test campaign involved a large test volume, totaling one-thousand devices, spread between several thermal qualifications and part screenings. Despite redundancy built into the VSS floodlights and other systems, the Restore-L team needed to fully characterize the part performance and ensure consistent operation throughout the mission lifetime. From an optoelectronics standpoint the quantity, redundancy, and component cost, meant that the screening and qualification was a relatively low-risk effort. The primary issue in testing such a large part quantity for spaceflight is efficiently and repeatedly characterizing performance across the entire screening group. To this objective, the Photonics Group developed new experimental setups that allowed large batches of parts to be tested consistently in a semi-automated fashion, while reducing the risk of Electro-Static Discharge (ESD) events and lead forming. Several subsets



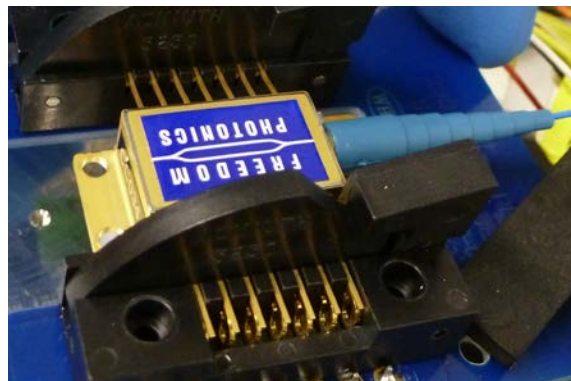
of the screening group were subjected to thermal qualification at hot and cold operational extremes, while radiation testing was performed on a final subset in an attempt to excite material displacement damage failure modes.

At the end of all long-term life testing and characterization efforts, more than nineteen gigabytes of electrical and optical performance data had been collected. Even in cases of low unit cost and high quantity of components, it is important to remember that screening test campaigns produce flight hardware—as such, proper process control and handling is critical to maintaining the flight-ready status of screened devices. Detailed procedural documentation, informed setup design, and technician oversight were powerful tools that enabled successful protection of screened hardware and consistent characterization amongst components. The Restore-L spacecraft is expected to launch in 2022 to Low Earth Orbit (LEO)<sup>19</sup>.

#### **4. TECHNOLOGY READINESS LEVEL MATURATION OF A TUNABLE PHOTONIC INTEGRATED CIRCUIT IN INDIUM PHOSPHIDE**

Indium Phosphide (InP) technology, relative to other III-V semiconductors, has grown over the last several decades to become the most developed substrate platform for Photonic Integrated Circuits (PICs). Due to monolithic integration of all active components, InP Photonic Integrated Circuits have less subcomponent interface complexity, allowing miniaturization at a reduced cost. InP PICs are applicable to fiber optic communications, free space communication, and spaceflight microwave photonics. In RF (radio frequency) photonics, this technology facilitates the transfer of the RF processing functions using the light domain where the signal is less susceptible to electro-magnetic interference<sup>21</sup>. By transferring RF processing to the miniature InP PICs, satellites utilizing microwave photonics can save on cost, size, weight, and power (CSWaP). This is crucial for high density hardware in cubesats and High Throughput Satellites (HTS), where tuning the bandwidth to specific regions is necessary<sup>22</sup>. Widely tunable InP PICs, like the one tested by the GSFC Photonics Group, can also be used for optical frequency synthesis with high precision, and can be applied to LiDAR applications for beam-steering and laser communications, where CSWaP is critical<sup>21</sup>.

The GSFC Photonics Group has been evaluating the InP tunable laser FP3015C manufactured by Freedom Photonics. The testing is designed to apply typical space flight environmental stresses to commercially available, off the shelf devices. The tests used to evaluate this device include: launch random vibration testing, thermal cycling and radiation. Five components were supplied to the Photonics Group for initial evaluation and one as a control to ensure stability and consistence of the testing experimental set ups.



**Figure 9:** Freedom Photonics Indium Phosphide Photonic Integrated Circuit Tunable Laser, FP3015C.

The team followed up with several correspondence meetings regarding acceptable parameters to monitor and validate the part performance. Prior to starting any testing, the components were inspected and baselined for proper parameter performance. The following is a summary table that lists the tests as conducted.

**Table 3:** Summary of environmental validation testing for the InP Photonic Integrated Circuit.

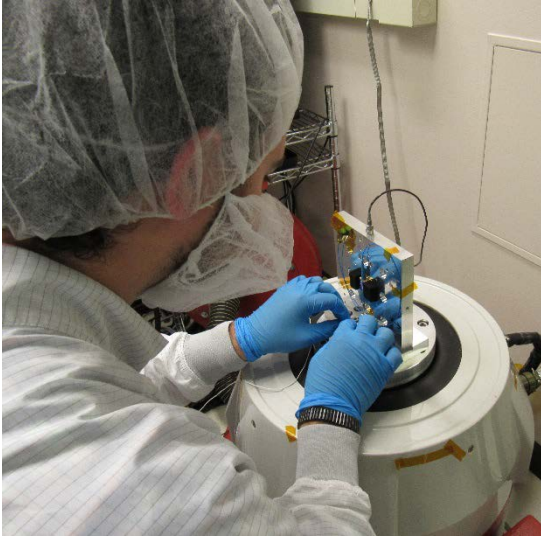
Test Name	Sample Number				
	CC026	CC027	CC028	CC029	CC032
Initial Characterization	X	X	X	X	X
Acceptance Level Vibration (GEVS 9.8 Grms)	X	X	X	X	X
Performance Characterization	X	X	X	X	X
Qualification Level Vibration (14.9 Grms)	X				X
Performance Characterization	X				X
Thermal Cycling & Characterization	X*	X	X	X	X*
Performance Characterization	X	X	X	X	X
Thermal Anomaly Investigation	X	X	X	X	X
Qualification Level Vibration (GEVS 14.1 Grms)		X	X	X	
Thermal Characterization for TEC bond check		X	X	X	
Packaging Construction Analysis on TEC bond	X				X

Three random vibration profiles (identified in Table 4) were used for the vibration portion of the verification testing; 1) GEVs acceptance level 9.8 Grms, 2) GEVs qualification level 14.1 Grms and 3) Commercial specification of 14.9 Grms. Table 4 more specifically identifies the details of those profiles<sup>22</sup>.

**Table 4:** Summary of the random vibration profiles identified in Table 3.

Frequency (Hz)	Level	Frequency (Hz)	Level	Frequency (Hz)	Level
20	0.013 G <sup>2</sup> /Hz	20	0.026 G <sup>2</sup> /Hz	20	0.032 G <sup>2</sup> /Hz
20-50	+6 dB/octave	20-50	+6 dB/octave	20-50	+8 dB/octave
50-800	0.080 G <sup>2</sup> /Hz	50-800	0.16 G <sup>2</sup> /Hz	50-600	0.200 G <sup>2</sup> /Hz
800-2000	-6 dB/octave	800-2000	-6 dB/octave	600-2000	-8 dB/octave
2000	0.013 G <sup>2</sup> /Hz	2000	0.026 G <sup>2</sup> /Hz	2000	0.033 G <sup>2</sup> /Hz
<b>Overall</b>	<b>9.8 Grms</b>	<b>Overall</b>	<b>14.1 Grms</b>	<b>Overall</b>	<b>14.9 Grms</b>

As is listed in Table 3, performance initial characterization was conducted prior to any exposure to applied stresses. After this initial characterization, the “acceptance” profile was conducted from Table 4, for 3 minutes per axis: in each x, y and z axis alignments. After which, the characterization was conducted before 2 of the components (identified in Table 3 as CC026 & CC032) went on to the “qualification” level profile of 14.9 Grms (commercial space flight specification) for 3 minutes per axis for all three axes. At no point during post vibration characterization testing did any anomalies occur.

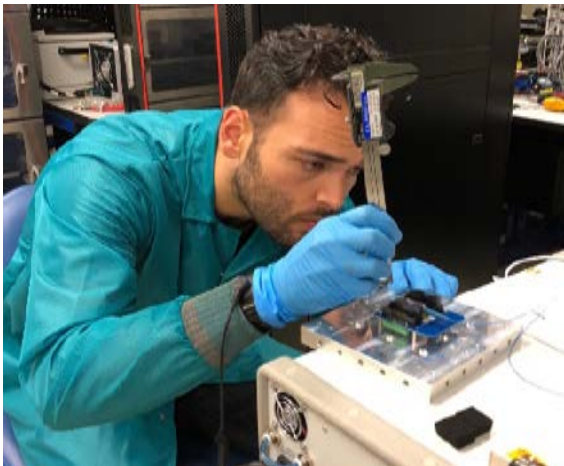


**Figure 10:** Alexandros Bontzos prepares the Photonic Integrated Circuit for random vibration testing.

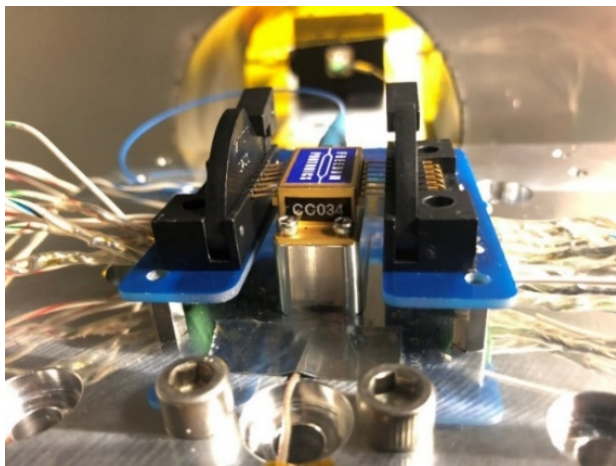


**Figure 11:** The device on the vibration fixture/shaker and ready to test.

During the subsequent thermal cycling test evaluations on the two devices (CC026 & CC032), an anomaly was identified regarding the thermal electric cooler for the laser diode at approximately 65°C. Once this was discovered, these devices were submitted for construction analysis to diagnose the issue such that a corrective action could be identified. The vendor is intending to ruggedize these devices to withstand higher random vibration qualification profiles in the future. The other devices, post thermal cycling testing were exposed to the GEVs qualification profile of 14.1 Grms as shown in table 3. Since it was expected that the anomaly would not show up in performance testing without enduring hot temperature exposure, a follow up thermal cycle test was conducted to evaluate the remaining 3 parts. These 3 parts did not show the anomaly identified as a result of the 14.1 Grms vibration profile. Without a statistical sample, it is a qualitative observation that while these commercial parts could endure a GEVs level qualification at 9.8 and 14.1 Grms without issue, the higher level profile of 14.9 Grms, did have an impact.



**Figure 12:** Cameron Parvini, prepares the thermal cycling test fixture for the InP Photonic Integrated Circuit



**Figure 13:** The InP device in configuration just prior to thermal cycling.

It is important to note that it is typical of commercial components off the shelf to perform in a similar fashion to these InP PIC devices. In light of the fact that these components are of greater complexity than typical laser diodes, their performance indicated that they were robust as an emerging photonic integrated circuit technology. Radiation proton

testing was conducted on two pristine devices and one of this evaluation lot. The results were promising. Further evaluation will be necessary.

## **5. OPTICAL FIBER SYSTEM FOR EUROPA CLIPPER MISSION POLARIZATION SENSOR: CRYOGENIC RADIATION VALIDATION**

The Europa Clipper Mission is extremely significant for a variety of reasons, one of which being is that it will enable the follow-up mission, the Europa Lander. Searching for signs of life in the universe has captured human fascination for decades, and remains an exceedingly difficult task in a harsh environment such as Europa<sup>23</sup>. As a result, the information collected by the Clipper mission will be vital to create successful designs for the Europa Lander. The Interior Characterization of Europa using Magnetometry (ICEMAG) instrument was a magnetometer utilizing scalar vector helium sensors dependent upon an optically polarized light delivery system. The objective of this sensor was to measure the magnetic fields around Europa to determine ice thickness, salinity and other parameters to determine life habitability on Europa<sup>24</sup>.

The most daunting task for the polarized light optical fiber delivery system, was how to transmit stable polarized light from the laser in the vault electronics box on the spacecraft structure (which the Applied Physics Labs at John's Hopkins University was responsible for) down a boom produced by Orbital ATK (now Northrup Grumman) to the magnetic sensors. The Jet Propulsion Laboratory (JPL) contacted NASA GSFC Photonics Group lead, Melanie Ott to confirm feasibility of the light delivery system. It is not unprecedented to use a set of optical fiber assemblies across a spacecraft and boom (extra-vehicular) to an instrument, as demonstrated by recent missions:

- The Lunar Reconnaissance Orbiter Laser Ranging experiment, which has currently been operational for more than ten years and is still functional even though the mission requirement was 14 months to 3 years<sup>25</sup>;
- The Mars Curiosity Rover, that had assemblies routed from the ChemCam optical input, through the twist caps, and over to the ChemCam processing spectrometer<sup>7</sup>.

Due to the different subsystem providers and integration plans, several interconnections were necessary in the design of the magnetometer light delivery system to facilitate an expedient integration process. The perceived radiation and temperature susceptibility of the extra-vehicular fiber optic assemblies along the boom and the corresponding weight and power accommodations were a great concern to the sensor instrument team. They were concerned that the sensor at the end of the boom, would not receive sufficiently stable polarized light to meet the end of life requirement during operations at Europa.

The first item identified by GSFC, was the over-design regarding weight and power to accommodate the light delivery system. In order to realize the cost savings of more than \$30M in weight and power reduction, the system required a comprehensive radiation study to prove this—testing that GSFC has done in the past as necessary<sup>26,27</sup>. Melanie Ott presented the fiber optic feasibility test results at the preliminary design review with a follow up engineering peer review two months later with a JPL panel. The sensor team and review panel, required the design feasibility demonstrated through testing and or heritage (technology readiness level of 9). Several key questions required answers during this review:

- 1) Does polarization-maintaining (PM) optical fiber work at cryogenic temperatures?
- 2) Which fiber and upjacketing or cabling materials would work for the extra-vehicular sections?
- 3) How much shielding and heating would be required to mitigate radiation darkening for Europa Clipper?

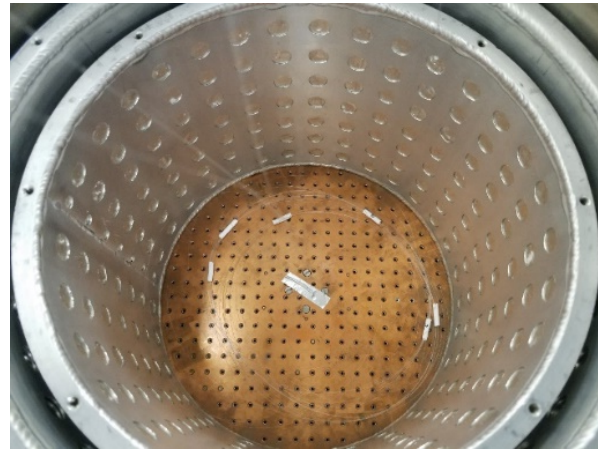
### **5.1 Polarization Maintaining Optical Fiber Functionality at Cryogenic Temperatures**

Since vendors often do not possess knowledge of how a product functions below its terrestrial specification thermal range, the question of how well the optical fiber would perform at cryogenic temperatures required verification. A cryogenic test was conducted to prove that optical fiber would maintain a sufficient Polarization Extinction Ratio (PER) down to cryogenic temperatures and determine which fiber option would be the best flight candidate. The test was designed to log the PER in-situ as the cryogenic chamber cooled down to -165°C. The polarization maintaining fiber

candidates did not change performance significantly at  $-165^{\circ}\text{C}$  (108K) or lower. Figures 14 and 15 show the test configuration to measure the PER of coated “bare” fiber during exposure to cold.



**Figure 14:** Alejandro Rodriguez-Perez sets up the PER data logging system with custom fiber optic thermal vacuum feedthroughs produced by the Photonics Group.



**Figure 15:** The fiber candidates inside of the cryogenic chamber shroud.

Table 5 summarizes the cryogenic validation test results regarding the polarization extinction ratio as compared to room temperature, pre-cryogenic stress exposure in an in-situ testing configuration.

**Table 5:** PER performance at cryogenic temperatures less than or equal to  $-165^{\circ}\text{C}$  (108K).

Candidate (10 m)	Room Temperature PER (dB)	Cold Temperature (dwell)	Change in PER (dB), as compared to $25^{\circ}\text{C}$
Coherent Nufern PM980-XP	27.3	$-205^{\circ}\text{C}$	0.40
Coherent Nufern PM980B-XP	23.8	$-165^{\circ}\text{C}$	0.20

Even as low as  $-205^{\circ}\text{C}$ , the fiber PER shifted 0.4 dB down and at  $-165^{\circ}\text{C}$  was 0.20 dB as compared to the PER prior to the stress being applied. During cryogenic testing, the optical fiber candidates were down-selected.

## 5.2 Flight Fiber Selection and Cable Choice

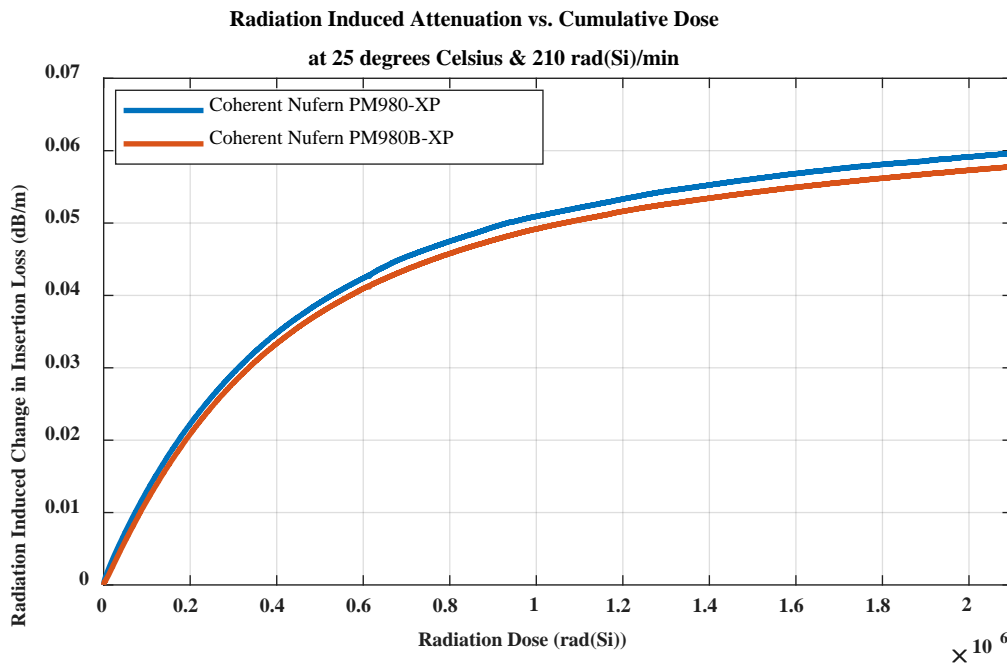
Testing and screening results from the cryogenic PER measurement were used to down-select from the original list of fiber candidates. Two of the original fiber types were eliminated due to issues with manufacturability during termination and for not being representative of the commercial standard as available on fiber coupled commercial components.

Fabrication of the Aft Optics Subsystem (AOS) Source Plate Assembly cryogenic cables for the James Webb Space Telescope and other thermal vacuum assemblies led to a cryogenic optical fiber jacketing solution that could be modified economically for Europa<sup>28,29</sup>. W.L. Gore Flexlite® could be used in areas of moderate thermal excursion, within the commercial specification. However, the extravehicular boom assemblies would be expected to function at temperatures as low as  $-165^{\circ}\text{C}$ . Previous studies performed by the Photonics Group provided an alternative that would be appropriate for the extra-vehicular application. At the time, the Photonics Group was also conducting testing validation for a custom fabricated thermal vacuum cable that would provide low attenuation at  $-120^{\circ}\text{C}$  for the GEDI Bench Checkout Equipment (BCE)<sup>28</sup>.

## 5.3 The Response of Optical Fiber to Radiation and Cryogenic Temperatures

JPL decided to “buy down” the risk as recommended by GSFC during 2018 preliminary design review, opting to test both the cryogenic and radiation performance of the optical fiber candidates for the light delivery system. The GSFC

Photonics Group designed and implemented a comprehensive radiation test rack, in addition to utilizing an ambient thermal chamber and cryogenic chamber to sustain operational temperatures in the gamma facility during in-situ testing. The objective was to collect the data necessary to generate a comprehensive radiation induced attenuation (RIA) model applicable for calculating radiation induced loss for any dose rate, total dose and temperature.

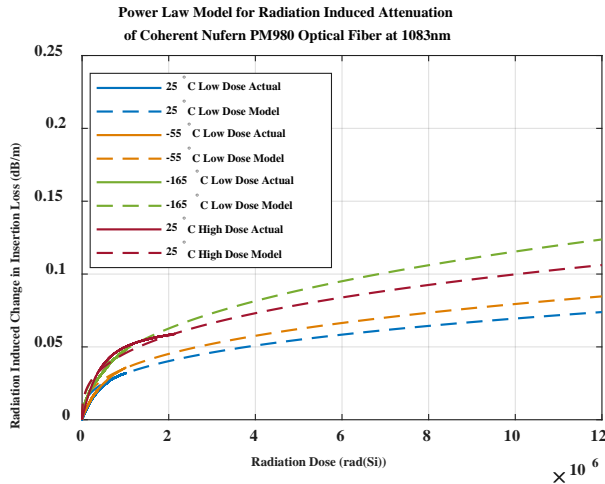


**Figure 16:** Radiation induced attenuation, approaching saturation behavior at 2.1 Mrads total dose, 210 rads/min Coherent/Nufern optical fiber PM980-XP & PM980B-XP at 25°C.

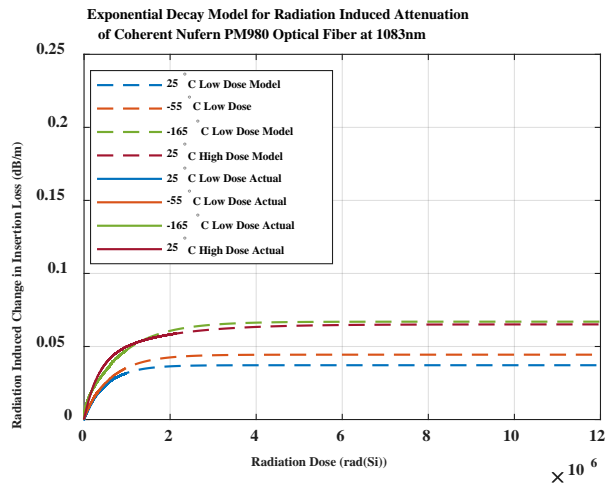
A power law equation is commonly used to generate an attenuation model of the form:  $A(D, \Phi) = C_0 \Phi^{1-f} D^f$ , where  $C_0$  is dependent upon dose rate and  $f$  is dependent upon temperature<sup>26</sup>. However, at lower dose rates and or total doses, the power law equation over-estimates the radiation induced attenuation. This is the reason why the Lunar Orbiter Laser Altimeter, Laser Ranging flight lot radiation model could not be used for extrapolating to Europa’s environment<sup>6</sup>. A room temperature test was conducted just prior to the sensor design review for demonstration of “saturation” behavior typical to optical fiber at high total dose and moderate dose rate. Saturation is the point at which radiation induced losses and annealing balance one another out, to reach a steady state. The purpose was to prove, even at a dose rate two orders of magnitude higher than an extra-vehicular assembly on the International Space Station (~1Mrad/year or 2 rad/min), that indeed saturation would occur if the test ran for long enough. In Figure 16, this behavior is evident. The performance of down-selected optical fiber candidates are shown in Figure 16 where radiation induced attenuation (dB/m) is graphed (dB/m on the y-axis) against total dose (rads on the x-axis). The dose rate of 210 rads/min at room temperature of 25°C for the fiber data in Figure 16. Ten meters of each type of fiber was used to illustrate saturation behavior and for choosing between the Coherent/Nufern PM980-XP and PM980B-XP candidates, if it mattered.

It is evident in Figure 16, that both fibers behave similarly and are approaching asymptotically a saturation of less than 0.07 dB/m. It is apparent that the fiber attenuation would inevitably reach saturation, where the losses stabilize regardless of the total dose. For monitoring the losses during the exposure, testing was conducted using 20 mW of transmitted optical power at a 1083 nm wavelength. The monitoring power level was determined based upon estimates of the optical power delivered to the furthest point away from the source, at the sensor (the worst case). The choice to use a “powered” test to monitor the fiber (as opposed to a “dark test” using less than 3 microwatts) was logical based upon the mission design, since a majority of the dosing would occur during operations upon arrival at Europa. It was required that the sensor operate once it had arrived at Europa and was the primary purpose of having the subsystem on-board.

It was proposed that the system would not need heaters or extra shielding since the light traveling at the lowest operational power levels would anneal the fiber sufficiently to compensate for a portion of the radiation induced attenuation, especially at the coldest extremes. A comprehensive combined thermal-radiation campaign was conducted after the room temperature testing. Figure 17 and 18 show the data as collected during the comprehensive thermal-radiation test.



**Figure 17:** Comprehensive Radiation Induced Attenuation using the Power Law Model



**Figure 18:** Comprehensive Radiation Induced Attenuation using the “exponential decay” model.

The results using the Power Law method for extrapolation are in Figure 17, where Figure 18 shows a more accurate version of providing an extrapolation model that better matches the saturation behavior of optical fiber in general. Both plots contain the raw data, further tracked with two different extrapolation models that extend the total dose exposure to 12 Mrads. In using the “test like you fly” methodology, it is evident that the polarization maintaining fiber as an off-the-shelf commercial product by Coherent/Nufern, performs sufficiently under conditions of doses higher than 12Mrads, at 210 rads/min while at a cryogenic temperature. The subject of accurate extrapolation at high total dose and moderate or low dose rates is the subject of a future paper. Keeping in mind that “moderate” dose rates refer to dose rates two orders of magnitude higher than outside of the space vehicles on International Space Station, with 2 rad/min in earth’s orbit as opposed to 210 rads/min as expected for the Europa Clipper. System analysis resulted in losses not exceeding 1 dB at the end of life for Europa Clipper sensor mission requirements, regardless of the model used to calculate the attenuation at 12Mrad.

To give more perspective regarding the ability of fiber to withstand harsh environments and to show how testing at low dose rates has been used to simulate long duration missions, Table 6 summarizes some past data.

**Table 6:** Overview of Radiation Induced Attenuation as provided by data or models over the past 20 years.

Location & Instrument	Dose Rate (rad(Si)/min)	Total Dose (rad(Si))	Temp (°C)	Wavelength (nm)	RIA for 10m (dB)
MERCURY Laser Altimeter (20 years ago)	11.2*	30 Krad	-24	850	1.0
MOON: LOLA on LRO (10 years ago)	1	5 Mrad	24	850	0.19
EARTH: ICESAT-2 Laser Altimeter	5.5	8 Krad	24	532	0.21
EUROPA Clipper	210	12Mrad	-165	1083	1.0**

\*extrapolation model not available due to thermal range too close

\*\*radiation induced attenuation based on system analysis & worst case power levels for monitoring

As the ability to capture in-situ data accurately improves (contingent upon funding), the modeling predictions can provide a better understanding of what can be expected under harsher radiation conditions like Europa. Table 6 shows a comparison between different fiber based instruments, normalized to a 10 meter length of fiber. The top three entries for the Mercury, the Moon and the Earth, are all multimode fibers used as part of a receiver system and were monitored using 3 microwatts or less of optical power. The last Europa entry shows much harsher environmental conditions. However, the Europa fiber optic system was designed for power delivery not photon counting. Therefore, for radiation loss risk mitigation, the “worst case” amount of transmitted power was used for monitoring during testing such that light induced annealing could reduce the losses but not overestimate the recovery.

The lesson learned over the years by monitoring radiation-induced effects on optical fiber has led us to the conclusion that system noise must be minimized, or the mathematical extrapolation model cannot be formulated. In the past, most data collection was dependent on available funding for the task. Radiation induced attenuation has never been a parameter that would break an optical system, it was just a parameter that needed to be verified per each flight lot for end of life calculations at the system level.

## 6. SUMMARY

Over the past ten years, new commercial technologies have emerged and been implemented into space flight applications successfully. Presented here is available test data and summary usage details. From large earth orbiting laser based altimeters and ranger systems to small yet extremely innovative emerging technologies like Photonic Integrated Circuit Indium Phosphide tunable lasers – all could be applied to the vision of the future Gateway, remote sensing for science, or navigation. When commercial technologies are unavailable, NASA GSFC can provide the partnerships to advance a component, an instrument or apply the risk mitigation strategies to either testing or production of a system in a cost effective manner to meet aggressive schedules. Our intent is for future collaborations to further the application of commercial technologies for space flight instrumentation. Please visit the website <https://photonics.gsfc.nasa.gov> for updates and more information.

## REFERENCES

- [1] Loff, S.: Explore Moon to Mars. National Aeronautics and Space Administration. <https://www.nasa.gov/topics/moon-to-mars> (2019). Accessed May 2019.
- [2] Sun, X. et al.: Space Lidar Developed at the NASA Goddard Space Flight Center – The First 20 Years. IEEE Journal Of Selected Topics in Applied Earth Observations and Remote Sensing, 2013.
- [3] Smith, D. et al.: Two-Way Laser Link over Interplanetary Distance. Science Magazine, ([www.sciencemag.org](http://www.sciencemag.org)) Vol. 311 (5757) January 6, 2006, pp 53.
- [4] Sun, X. et al.: Simultaneous laser ranging and communication from an Earth-based satellite laser ranging station to the Lunar Reconnaissance Orbiter in lunar orbit. Proc. SPIE Volume 8610, Free-Space Laser Communication and Atmospheric Propagation XXV, March 2013.
- [5] Ott, M. et al.: Optical Fiber Cable Assembly Characterization for the Mercury Laser Altimeter. Proc. SPIE 5104, Enabling Photonic Technologies for Aerospace Applications V, July 2003
- [6] Ott, M. et al.: The Optical Fiber Array Bundle Assemblies for the NASA Lunar Reconnaissance Orbiter, Evaluation Lessons Learned for Flight Implementation. Invited paper at the International Conference on Space Optics, Fiber/Free Space Optics, Toulouse France, October 2008.
- [7] Lindensmith, C. et al.: Development and Qualification of a Fiber Optic Cable for Martian Environments. Invited paper at the International Conference on Space Optics, Rhodes Island Greece, October 2010.
- [8] Amzajerdian, F. et al.: Demonstration of coherent Doppler lidar for navigation in GPS-denied environments. Proc. SPIE 10191, Conference on Laser Radar Technology and Applications XXII, May 2017.
- [9] Carson, J. et al.: The SPLICE Project: Continuing NASA Development of GN&C Technologies for Safe and Precise Landing. American Institute of Aeronautics and Astronautics (AIAA) Scitech 2019 Forum, January 2019.
- [10] Keeseey, L.: Robotic Satellite Servicer Could Bring New Life to Old Satellites. NASA, 13 Feb. 2018, [www.nasa.gov/feature/goddard/2018/self-driving-servicer-now-baselined-for-nasa-s-restore-l-satellite-servicing-demonstration](http://www.nasa.gov/feature/goddard/2018/self-driving-servicer-now-baselined-for-nasa-s-restore-l-satellite-servicing-demonstration)



- [11] Ott, M. et al.: The fiber optic system for the Advanced Topographic Laser Altimeter System (ATLAS) instrument. Proc. SPIE 9981, Planetary Defense and Space Environmental Applications, August 2016.
- [12] Wake, S. et al.: Optical system design, integration, and alignment of the Global Ecosystem Dynamics Investigation LiDAR. to be published SPIE Vol. 11128, Aug 2019.
- [13] Stysely, P. et al.: Laser production for NASA's Global Ecosystem Dynamics Investigation (GEDI) LiDAR. Proc. SPIE 9832, Laser Radar Technology and Applications XXI, May 2016.
- [14] Edwards, R. et al.: ICESat-2 Laser Technology Development. Proc. SPIE 8872, LiDAR Remote Sensing for Environmental Monitoring XIV, Sept 2013.
- [15] Storm, M., Hovis, F.: IEEE Aerospace Conference Space Lidar Technologies Conference Supporting Upcoming NASA Earth Science & Laser Communications Missions. 2015 IEEE Aerospace Conference, March 2015.
- [16] Blau, P.: OSIRIS-REx Instruments. Spaceflight 101 (<http://spaceflight101.com/>). <http://spaceflight101.com/osiris-rex/osiris-rex-instruments/> (2019). Accessed April 2019
- [17] Morton, E.: NASA's Newly Arrived OSIRIS-REx Spacecraft Already Discovers Water on Asteroid. OSIRIS-REx Asteroid Sample Return Mission (<https://www.asteroidmission.org/>). <https://www.asteroidmission.org/?latest-news=nasas-newly-arrived-osiris-rex-spacecraft-already-discovers-water-asteroid> (2018). Accessed April 2019
- [18] Alessandro, A., Hall, L.: NASA's Restore-L Mission to Refuel Landsat 7, Demonstrate Crosscutting Technologies. National Aeronautics and Space Administration. <https://www.nasa.gov/feature/nasa-s-restore-l-mission-to-refuel-landsat-7-demonstrate-crosscutting-technologies> (2016). Accessed April 2019
- [19] Reed, B.: Restore-L. NASA Satellite Servicing Projects Division. <https://sspd.gsfc.nasa.gov/restore-l.html>. Accessed April 2019
- [20] Zhao, H. et al.: High Power Indium Phosphide Photonics Integrated Circuits. IEEE Journal Of Selected Topics in Quantum Electronics, April 2019.
- [21] How to Enhance a High Throughput Satellite (HTS) Using Beam Hopping. Bliley Technologies. [blog.bliley.com/high-throughput-satellite-beam-hopping](http://blog.bliley.com/high-throughput-satellite-beam-hopping) (17 November 2017). Accessed May 2019
- [22] General Environmental Verification Standards (GEVS). NASA Goddard Space Flight Center. <https://standards.nasa.gov/standard/gsf/gsf-std-7000> (April 2019). Accessed April 2019
- [23] Phillips, C.B. et al.: Europa Clipper Mission Concept: Exploring Jupiters Ocean Moon. Earth and Space Science News: EOS Volume 95, Issue 20, May 20, 2014, pp 165-167.
- [24] Raymond, C. et al.: ICEMAG. Aug 24 2015, Presentation to the Outer Planets Assessment Group: Lunar and Planetary Institute, (OPAG). [https://www.lpi.usra.edu/opag/meetings/aug2015/presentations/day-1/8\\_g\\_raymond.pdf](https://www.lpi.usra.edu/opag/meetings/aug2015/presentations/day-1/8_g_raymond.pdf) (August 2015).
- [25] Petro, N.E., Keller, J.M., Cohen, B.A. et al: Ten Years of the Lunar Reconnaissance Orbiter: Advancing Lunar Science and Context for Future Lunar Exploration. Proc. USRA 50th Lunar and Planetary Science Conference, LPI Contrib. No. 2132 (2019).
- [26] Ott, M.: Fiber optic cable assemblies for space flight II: thermal and radiation effects. Proc. SPIE 3440, Photonics for Space Environments VI, October 1998. <https://doi.org/10.1117/12.326697>
- [27] Jin, X. et al.: Space Flight Qualification on a Novel Five-fiber Array Assembly for the Lunar Orbiter Laser Altimeter (LOLA) at NASA Goddard Space Flight Center. SPIE Optics and Photonics Conference, Photonics Technology for Space Environments II, Vol. 6713, Aug 28, 2007.
- [28] Thomes, W.J. et al.: Cryogenic fiber optic assemblies for spaceflight environments: design, manufacturing, testing, and integration. Proceedings for the SPIE Optical Engineering + Applications Conference, August 2016.
- [29] Gallagher, B., Knight, S., Barto, A., Thomes, W.J., Ott, M.: JWST ASPA fiber optic development for testing at 2.12 um. SPIE Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation, Vol 9151, August 2014.