Optoelectronics for Space Flight Instruments

Melanie N. Ott
NASA Goddard Space Flight Center
Engineering Technology Directorate

NASA Electronic Parts and Packaging Program
Workshop
June 16 2020

https://photonics.gsfc.nasa.gov

Meet the Photonics Group of NASA Goddard

Over 20 years of space flight hardware development, testing, & integration

Back row L-R: Erich Frese, Joe Thomes, Marc Matyseck
Middle row L-R: Rick Chuska, Eleanya Onuma, Cameron Parvini, Rob Switzer
Front row L-R: Hali Jakeman, Melanie Ott, Diana Blair

Trevon Parker

Alexandros Bontzos

Clairy Reiher

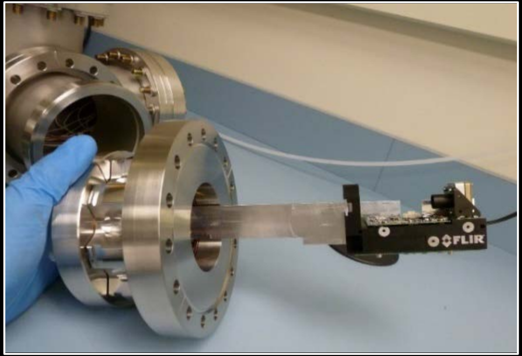
Alejandro Rodriguez

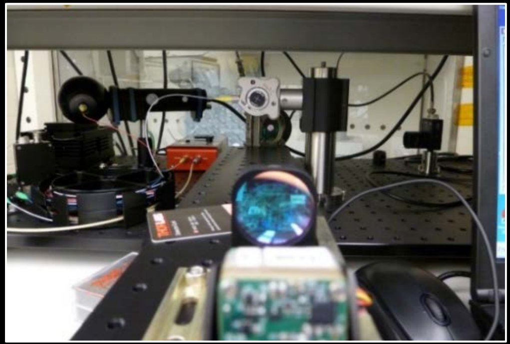
All great things require a great team!

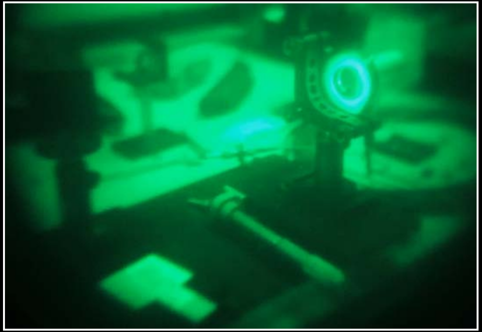
https://photonics.gsfc.nasa.gov

Outline

- Introduction
- Optoelectronics: 10 year screening and qualification overview
- Technology Maturation for Photonic Integrated Circuit
- Optoelectronics Testing Guide
- Summary
- Conclusions



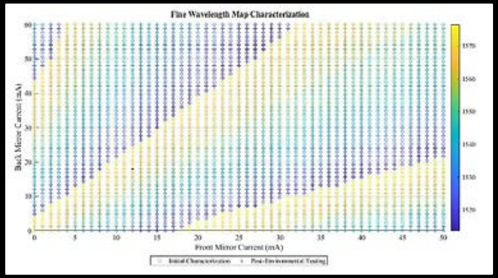


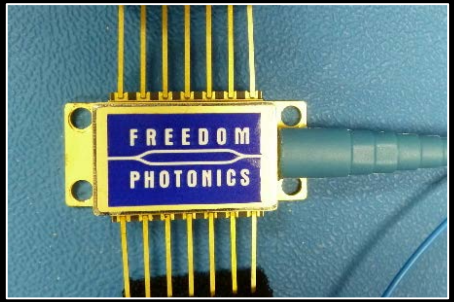


Tunable Lasers for Orbiter Communications

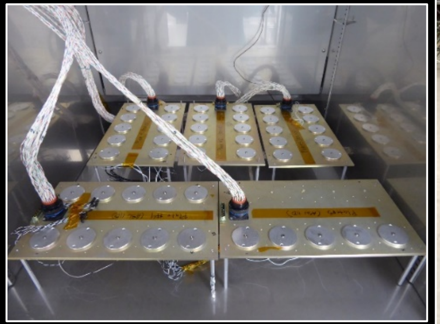
COTS LiDARs for Lander – & Autonomous Rendezvous

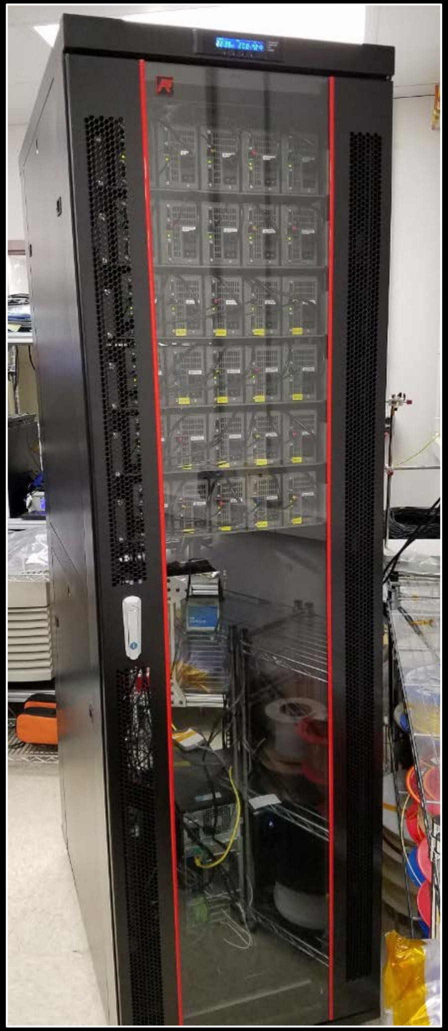
Detectors for Rover Spectroscopy



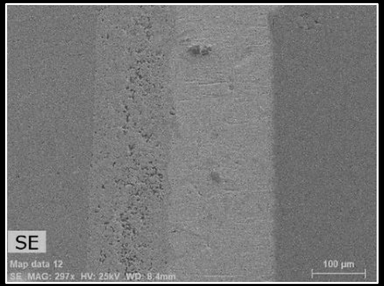


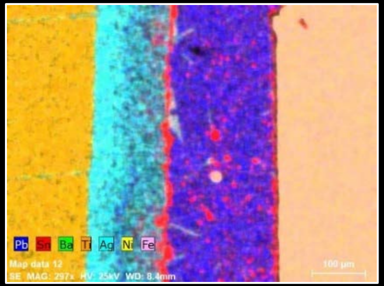
Screening and Qualification of Optoelectronics & Photonics for Space Flight



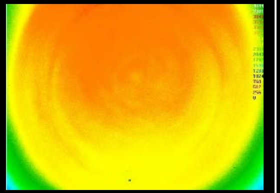


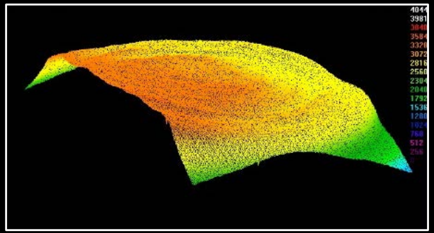
CODE 562
PHOTONICS
Goddard Space Flight Center



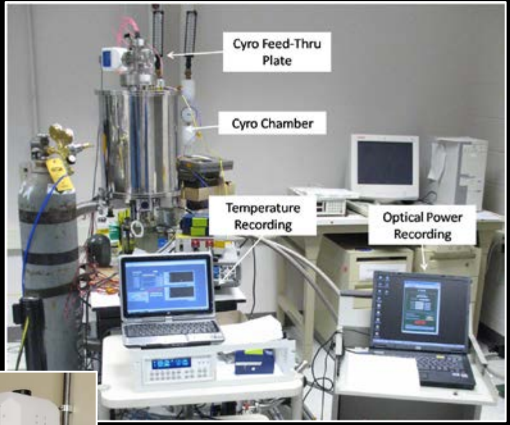


10 k X Mag SEM & Material Identification





LED Beam Profile



Cryogenic Test Facility

Materials Screening / Construction Analysis

→ **Optical Inspection & Screening**

→ **Performance Characterization**

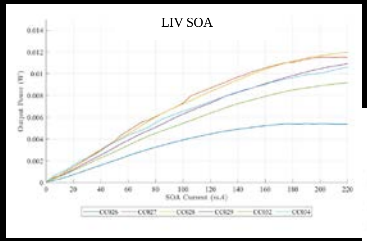
→ **Vibration / “Shock” Testing**

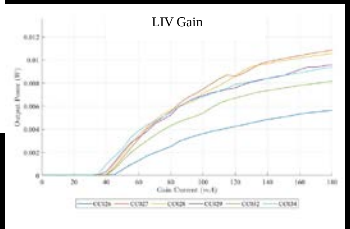
→ **Thermal Cycling / Vacuum**

→ **Radiation Testing**

→ **Additional Testing?**

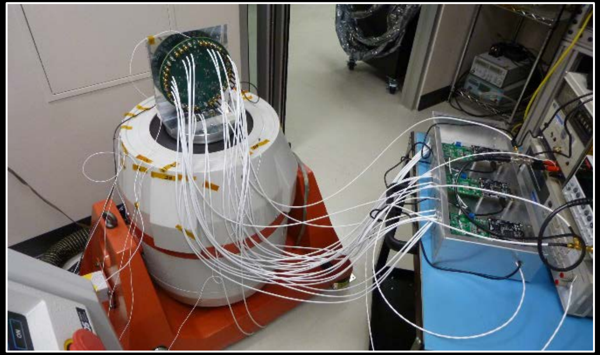
Optical Power, Current, Voltage Characterization





Radiation Test Equipment

White Light LED Testing in Environmental Chamber



Random Vibration Test & Shock Equipment

Issues to Consider

- Schedule, shorter term
- Funds available,
- Identify sensitive or high risk components.
- System design choices for risk reduction.
- Packaging choices for risk reduction.
- Quality by similarity means no changes to part or process.
- Qualify a “lot” by protoflight method—you fly the parts from the lot qualified, not the tested parts.
- Telcordia certification less likely now for non communication type applications.
- Process changes at the component level happen often.

Reference: ***Optical Society of America Frontiers in Optics, Session on Space Qualification of Materials and Devices for Laser Remote Sensing Instruments I, Invited Tutorial,*** **M. Ott, September 2007.**

Define "Qualification"

Are you rich or are you poor?

- $$$$= MIL-STD's + Telecordia + NASA or Space Requirements
  - Lifetime Lot buys for COTS parts or anything that will go obsolete.
- $$$ = Telecordia + NASA or Space Requirements
  - Buy critical parts , qualify by Lot.
- $$ = COTS Approach for Space Flight (NASA Requirements)
  - Requires careful planning especially with materials selection
  - Lot specific testing
  - Destructive physical analysis/ packaging or construction analysis necessary early on
  - Radiation testing performed early in selection phase – saves schedule later.

Reference: ***Implementation and Qualification Lessons Learned for Space Flight Photonic Components, Invited Tutorial*** **M. Ott, International Conference on Space Optics, Rhodes Greece, October 2010.**

CODE 562 PHOTONICS Goddard Space Flight Center

Optoelectronics Mission Highlights: last 10 years

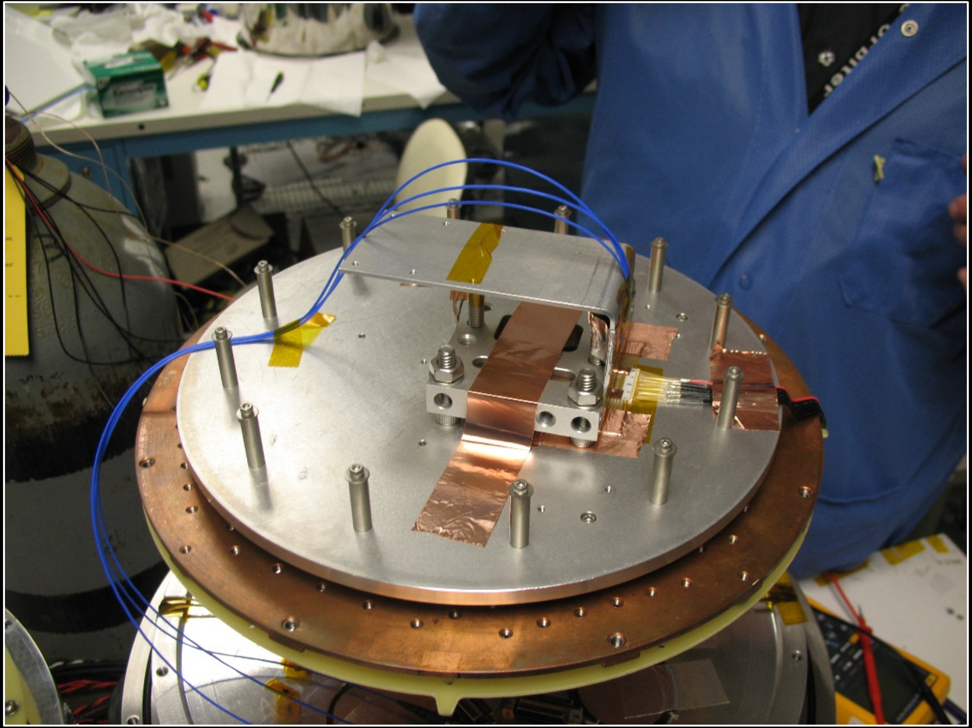
(communications transceivers not included in table)

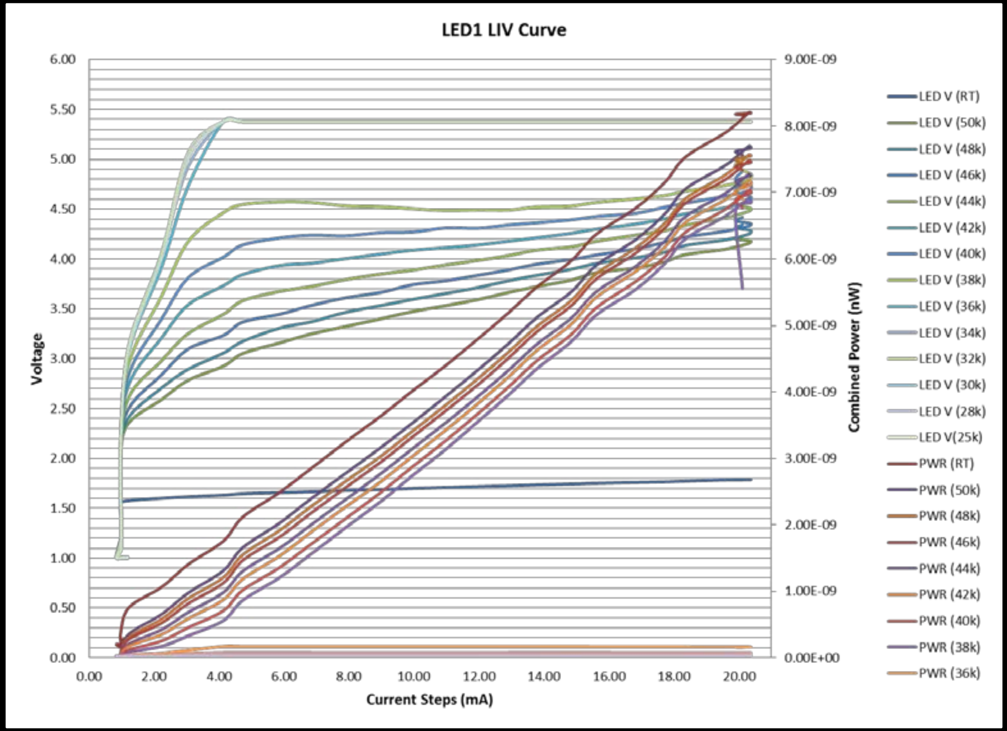
Project	Part Type	Wavelength (nm)	Quantity	Dates	Screening	Qualification	Radiation	Packaging Analysis
SAA Harris	Laser Diode	635, 660	30	2009	x	x		x
JWST	LED	633	6	2009		x		
TSIS/GLORY	Photodiode	140 – 1100	25	2010	x			x
LADEE/MAVEN	LED	450 – 650	50	2010	x	x		
SSCP	LED	450 – 650	290	2012	x	x		x
GOES-R	LED	315	4	2012				x
ATLAS	Photodiode	400 – 1100	10	2013	x		x	
OTES	Photodiode	450 – 1050	60	2014	x	x		x
OTES	Pyroelectric Detector	4000 – 50000	8	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 Circuit	1550	8	2018 - Present	x	x	x	x

James Webb Space Telescope (JWST)

- LEDs were evaluated for use in a cryogenic environment.

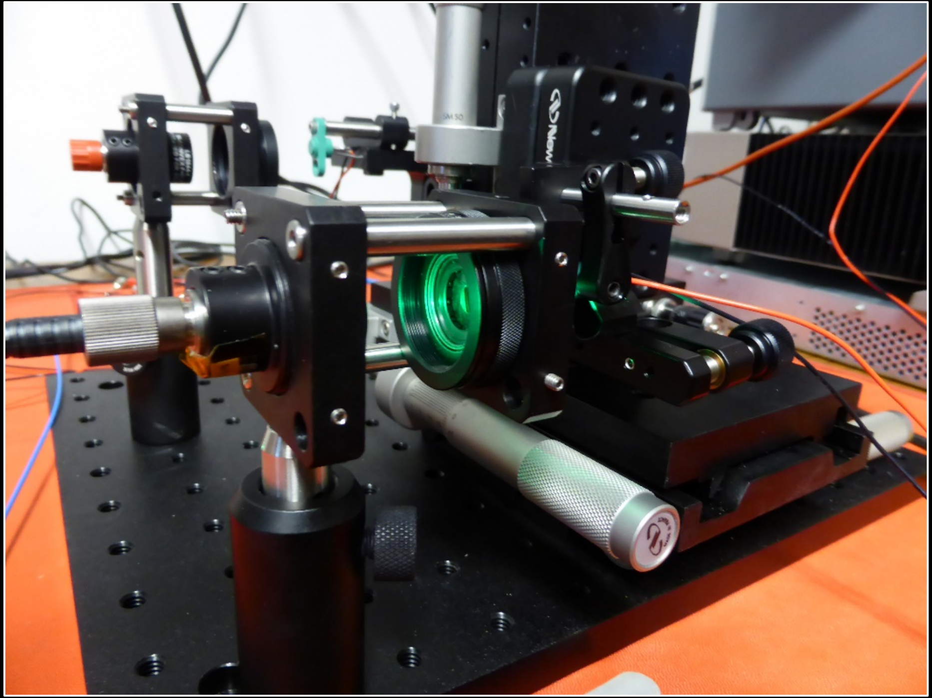
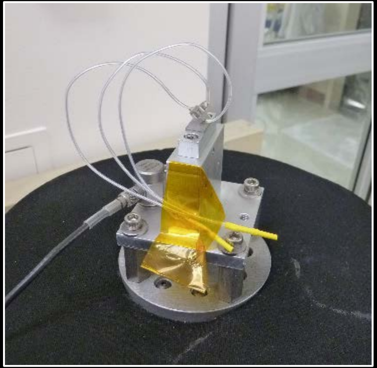
- In-situ electro-optical measurements were acquired to assess the component's performance characteristics.

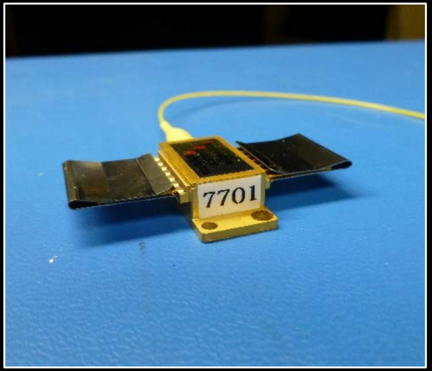


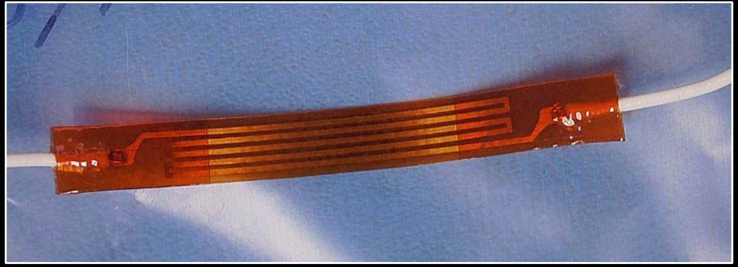


Ice, Cloud and Land Elevation Satellite (ICESat-2) – (ATLAS) Advanced Topographic Laser Altimeter System

- The Code 562 Photonics Group performed testing/evaluation of seven components used on the ATLAS instrument, currently operating on ICESAT-2.
- Testing included: visual inspections; thermal, electrical, and optical characterization; random vibration; radiation testing; and destructive physical analysis.

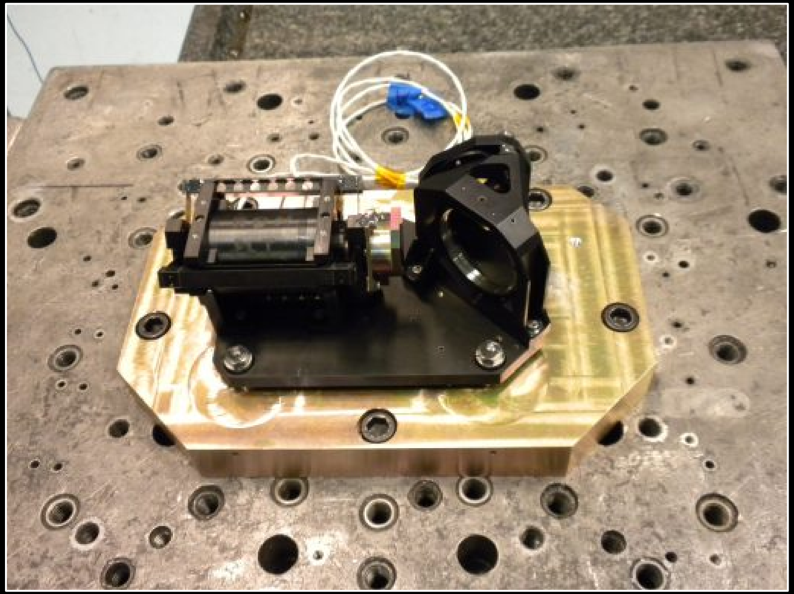


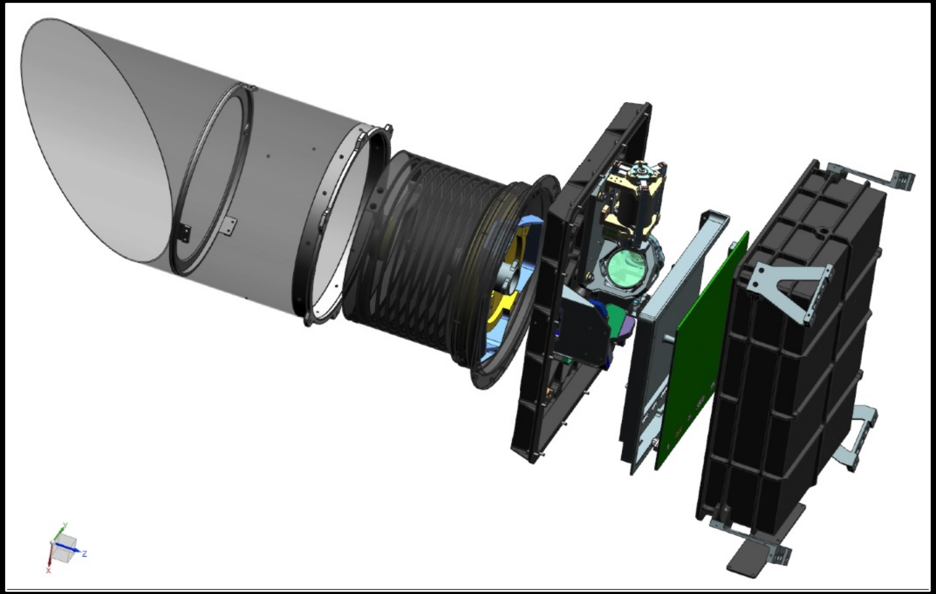



The Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) Mission to Bennu

The Thermal Emission Spectrometer (OTES) instrument is a point spectrometer on board (OSIRIS-REx) spacecraft.

- It is capable of mapping the asteroid Bennu's material composition, with a 4-50 um wavelength range. (arrived dec 2018, evidence of water determined.)
- OTES; developed at the School of Earth and Space Exploration at Arizona State University.



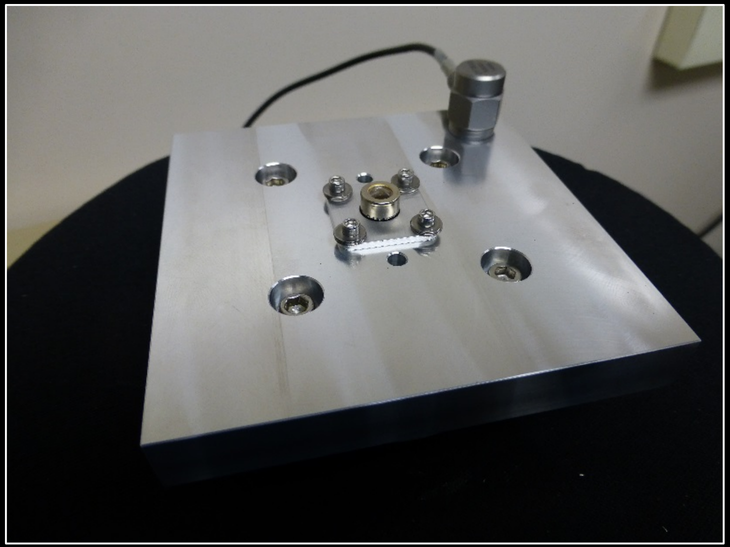


Reference: http://spaceflight101.com/osiris-rex/osiris-rex-instruments/

Partnership with Arizona State University Screening and Qualification

ASU partnered with the Code 562 Photonics Group to perform the screening and qualification of laser diodes, pyroelectric detectors, and photodiodes for;

- Thermal Emission Spectrometer,
- Space Act Agreement (Mars environment)
- Currently on "Lucy" (mission to Jupiter Trojans).

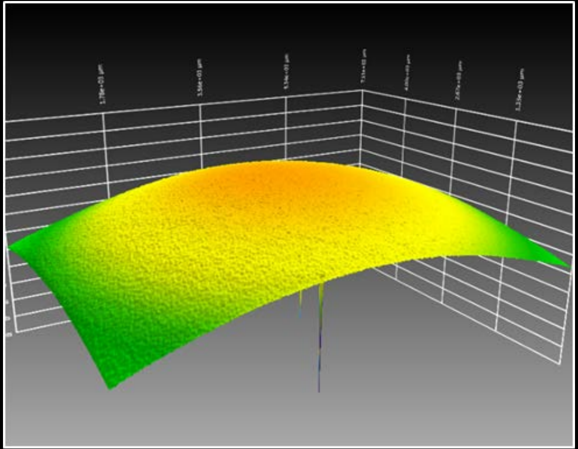


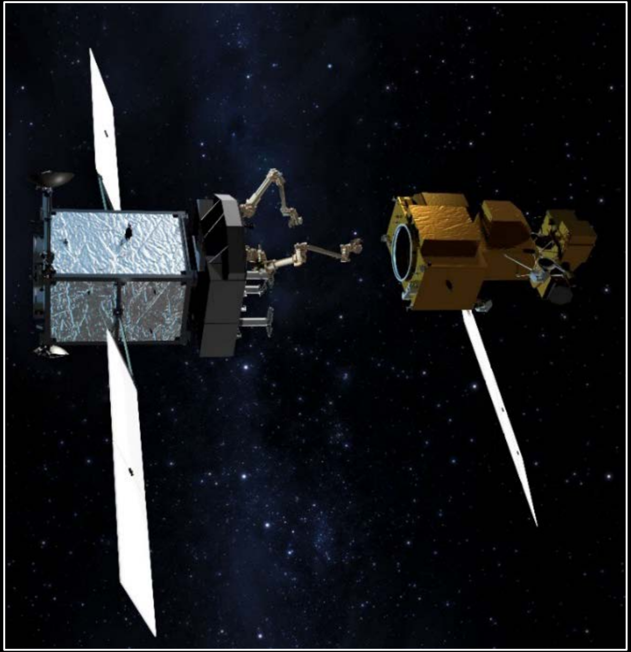
Vision Sensor Subsystem (Restore-L) Satellite Servicing Mission

The Restore-L spacecraft is a satellite servicing platform that can rendezvous, redirect, refuel, and thus enable missions to operate beyond their designed lifetimes. (refuel Landsat-7)

We provided: screening & qualification- white LEDs for Vision Sensor Subsystem (VSS), used to illuminate targets for docking, arm maneuvering, and other servicing tasks.

We are currently working on the LiDAR "Kodiak" to enable autonomous robotic docking





Reference: https://www.nasa.gov/feature/nasa-s-restore-l-mission-to-refuel-landsat-7-demonstrate-crosscutting-technologies

Indium-Phosphide, Photonic Integrated Circuit (PIC) Evaluation

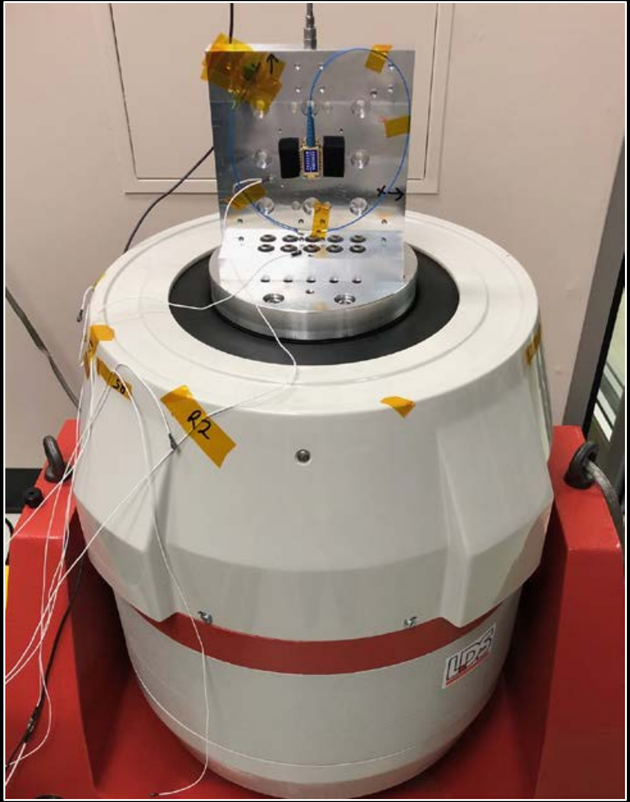
Funded by Space Technology Mission Directorate Game Changing Program
Radiation Testing Funded by NEPP

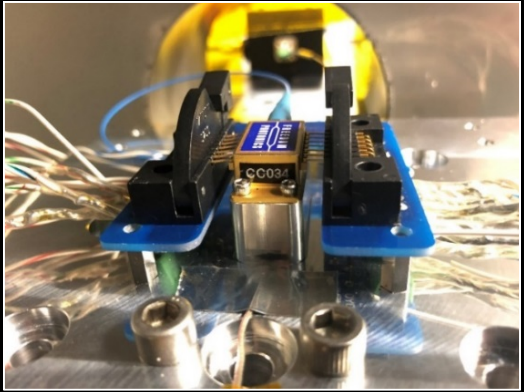
Motivation

- Demand for high-reliability, low size, weight and power (SWaP) for RF/Photonics. This is an emerging technology.
- This is for the purpose of technology maturation to enhance the "Technology Readiness Level" TRL.

@ GSFC Evaluation of the Freedom Photonics Tunable Laser

- Vibration, thermal cycling, and radiation testing (planned).
- Repeatable, low system noise characterization.
- Expertise in risk assessment and quick anomaly resolution.





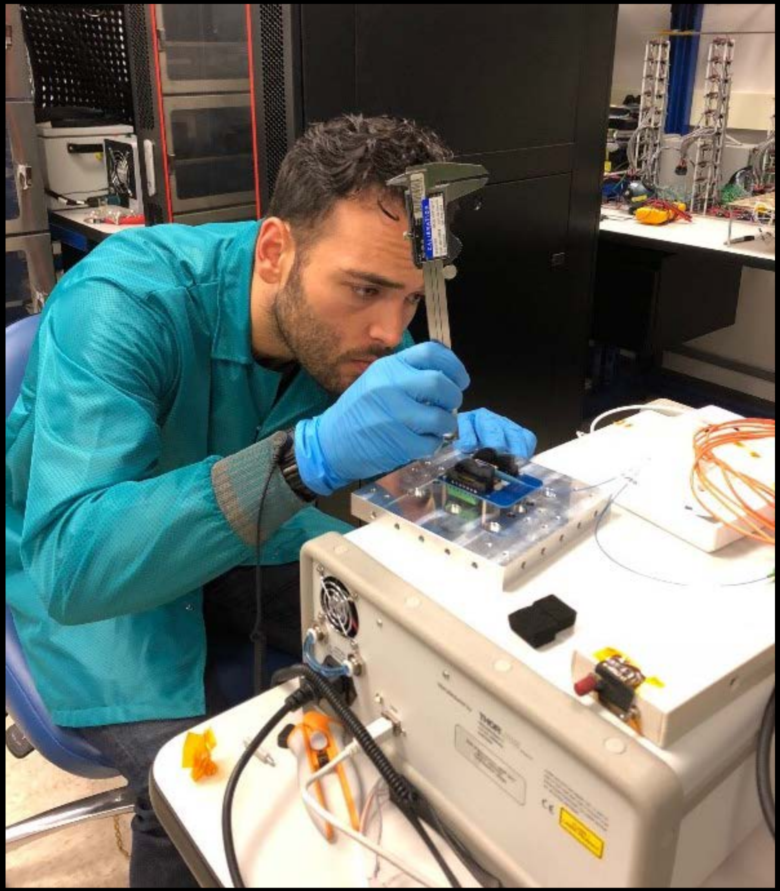
Indium-Phosphide Photonic Integrated Circuit Evaluation – HQ Game Changing Program Technology Readiness Level Maturation Test Campaign Summary

Procedure	Sample Number							
	CC026	CC027	CC028	CC029	CC032	CC034	CC061	CC062
Initial Performance Characterization	X	X	X	X	X	X	X	X
Acceptance Level Vibration (GEVS 9.8 Grms)	X	X	X	X	X			
Performance Characterization	X	X	X	X	X	X		
Qualification Level Vibration (14.9 Grms) Commercial	X				X			
Performance Characterization	X				X	X		
Thermal Cycling & Characterization	X*	X	X	X	X*			
Performance Characterization	X	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			
Radiation Testing			X				X	X

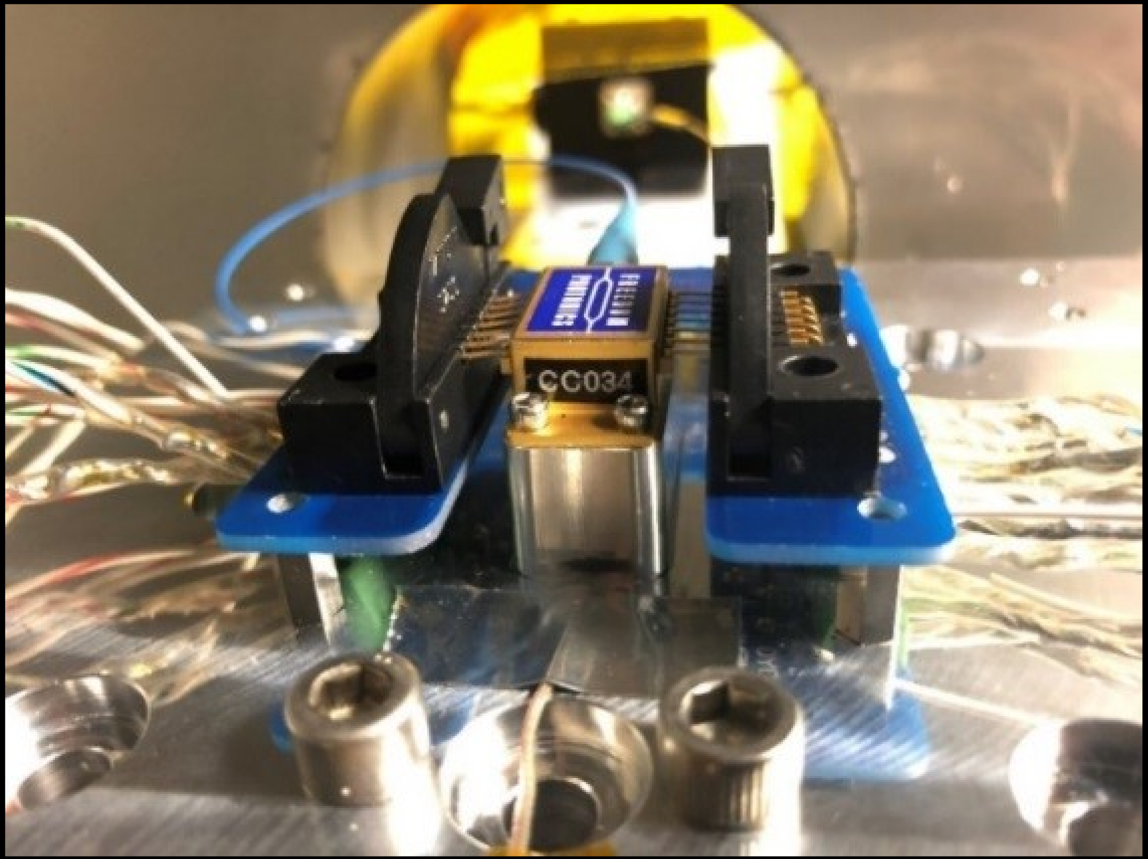
1) Environmental details will be explained later in this report; 2) CC034 was used as a "control" to verify test setup system stability. 3) TEC = Thermal Electric Cooler; 4) * Anomaly on TEC Behavior ; X = Completed

This is typical performance of a COTS device when enduring flight qualification.

Freedom Photonics InP PIC Thermal Cycling Preparations & Characterization



Cameron Parvini prepares the thermal cycling test fixture for the InP Photonic Integrated Circuit



The InP device in oven configuration just prior to thermal cycling. The custom device test mounting shown was fabricated by Photonics Group staff.

Random Vibration Qualification Profile Levels

Acceptance level
GEVS
Random Vibration,
3 minutes per axis (X,Y,Z)

Frequency (Hz)	Level
20	0.013 G^2/Hz
20-50	+6 dB/octave
50-800	0.080 G^2/Hz
800-2000	-6 dB/octave
2000	0.013 G^2/Hz
Overall	**9.8 Grms**

All 5 samples were exposed to this level.

Qualification level
GEVS
Random Vibration,
3 minutes per axis (X,Y,Z)

Frequency (Hz)	Level
20	0.026 G^2/Hz
20-50	+6 dB/octave
50-800	0.16 G^2/Hz
800-2000	-6 dB/octave
2000	0.026 G^2/Hz
Overall	**14.1 Grms**

All 5 samples were exposed to this level.

Qualification level
Commercial Satellite Specification
Random Vibration,
3 minutes per Axis (X,Y,Z)

Frequency (Hz)	Level
20	0.032 G^2/Hz
20-50	+8 dB/octave
50-600	0.200 G^2/Hz
600-2000	-8 dB/octave
2000	0.033 G^2/Hz
Overall	**14.9 Grms**

2 samples were exposed to this level, TEC anomaly.

Reference: General Environmental Verification Standard, for GSFC Flight Programs and Projects, GSFC-STD-7000, http://msc-docsrv.gsfc.nasa.gov/cmdata/170/STD/GEVS-STD-7000.pdf

Optoelectronics (Laser Components) Screening & Qualification Document draft in process

SECTION O1 OPTOELECTRONICS

INTRODUCTION

Optoelectronics are a subset of photonic components generally and can be succinctly described as any component that interfaces between electrical and optical energy. Optoelectronics exist in parallel to two other major laser component subcategories: waveguides (including classical optics, fiber optics, or any other component that manipulates light), and hybrid integrated devices that combine features of waveguides and optoelectronics (e.g. photonic integrated circuits). Subcategories within optoelectronics include sources, detectors, and modulators, which can each be broken into further subsets that represent unique combinations of operating principle, packaging, and performance specifications.

This section presents general guidelines on the design of effective screening and qualification test campaigns for optoelectronic components. Many organizations have attempted to compile testing frameworks that cover these devices, including the European Space Agency (ESA), military contractors, the NASA, and many professional organization working groups. However, the rate at which optoelectronic technology is created and matured makes it very difficult to maintain a "current" set of requirements, and the wide array of subcategories within optoelectronics create an unreasonable number of permutations to cover in quasi-static documentation. As a result, section O1 suggests campaign design methodologies that have proven effective in exciting a variety of component failure modes during environmental testing but is not intended as a comprehensive list. Instead, it outlines the methodology used to design and execute spaceflight screening and qualification campaigns.

The most appropriate test plans take care to evaluate the impact of mission-specific parameters (risk, budget, schedule, etc.) when deciding which evaluations to include, highlighting the balance of both cost and schedule with risk. In addition, the type of device being considered plays a large role in what style of evaluations are "necessary", leading to a more organic test campaign development process than standard EEE parts. As such, an example has been provided in Table 1 for a simple encapsulated light emitting diode (LED) for a ground support mission that is willing to accept higher risk levels (or has built in adequate redundancy).

While not recommended verbatim, MIL-STD-883 provides a helpful starting point for test conditions in the absence of strict requirements, and should be modified where possible to prevent significant, irreversible performance degradation. Additionally GSFC-STD-7000, alternatively known as the Goddard Environmental Verification Standards (GEVS), can be utilized for guidance where mission requirements appear insufficient. During screening (and qualification), failed components should be considered for immediate destructive physical analysis (DPA) to determine the exact failure mode.

In addition to the mission-level risk, there are component-level risks to performing screening and qualification testing that is too extreme for a given application. Especially given the fragile nature of the optical lensing and junction materials used in many source and detector components, care must be taken to test within a reasonable range of environmental requirements for a given mission without excessive margin. For example, LEDs or laser diodes with an optical window (or encapsulant) could be cracked from the extreme temperature shocks used in MIL-STD-883 Method 1011, causing optical and hermetic failure of the component. Unless the application truly requires that these parts be subjected to drastic thermal shifts in short time periods, Method 1010 (or alternatively slower temperature cycling) can be effectively used for component screening, with more aggressive testing left to the small-batch qualification campaign. This is true of other environmental testing as well, including vibration, burn-in, radiation, etc.

The number of components dedicated to each round of testing should be representative of the mission risk posture. For lower risk missions with tight budget requirements, smaller lot sizes (i.e. less statistical information) leads to higher risk that latent failures are not captured during the screening, and the qualification is less representative of the overall component lot. Such applications require system-level compensation (if possible) to include redundancy and allow for possible failures. Conversely, larger missions that are less cost constrained should perform the screening and qualification testing using as many components as reasonably affordable (in both budget and schedule) to acquire more statistical information on part performance. Under such circumstances, some redundancy can be avoided and the system may be more streamlined.

Table 1. Generalized LED Screening Test Plan (GSE)

Test	Test Sequence	Test Methods, Conditions, and Requirements
1	External Visual Inspection	MIL-STD-883, Method 2009 (minimum 10X)
2	Elemental Material Analysis	Use XRF/SEM/EDS procedures as applicable. Investigate external metallic surfaces for prohibited materials (Cadmium, Selenium, unleaded Tin, etc.)
3	Serialization	
4	Electro-Optical Performance Testing	Evaluate electrical and optical performance under in-situ electrical conditions. **1/**
5	Thermal Impedance Testing	MIL-STD-750, Method 3101.5. **2/**
6	Temperature Cycling	MIL-STD-883, Method 1010, Condition A, 10 Cycles minimum
7	Electro-Optical Performance Testing	Evaluate electrical and optical performance under in-situ electrical conditions. **1/**
8	PIND	MIL-STD-883, Method 2020, Condition A
9	Electro-Optical Performance Testing	Evaluate electrical and optical performance under in-situ electrical conditions. **1/**
10	Burn-in	MIL-STD-883, Method 1015, Condition B Use nominal operational temperature, ±5ºC Minimum 240 hours
11	Electro-Optical Performance Testing	Evaluate electrical and optical performance under in-situ electrical conditions. **1/**
12	Seal (Hermetic Types only) a. Fine Leak b. Gross Leak	MIL-STD-883, Method 1014 Condition CH or B (or A as Alternate) for Fine Leak Condition CH, B3, or C4 for Gross Leak
13	Electro-Optical Performance Testing	Evaluate electrical and optical performance under in-situ electrical conditions. **1/**
14	External Visual	MIL-STD-883, Method 2009 (minimum 10X)
15	Select Qualification Candidates	Select candidate components for qualification testing based upon performance and significant changes throughout screening.

Notes:

1/ Optional: also evaluate performance at component operational temperature extremes. Reserved for cases when the performance characteristics at thermal extremes are critical to successful operation.

2/ While not frequently addressed, it is occasionally requested at the Project's discretion to inform the thermal system design.

Table 2. Common Screening Tests

Test Name	Relevant Standard	Justification
External Visual Inspection	MIL-STD-883, Method 2009	Inspections are necessary at least to begin and end screening, and provide a visual baseline for both construction quality and the effects of environmental testing on the component's structural integrity.
Elemental Material Analysis	-	Visual materials analysis, using X-Ray Fluorescence (XRF) or similar tools, can avoid latent failures due to the inclusion (or inadvertent introduction of) materials prohibited from spaceflight; silicones, pure tin, cadmium, or other substances can be easily spread from a component to the lab environment, and subsequently to other critical flight items. Testing should occur early (usually in tandem with visual inspection).
Electro-Optical Performance Testing	-	Evaluating the device performance and IV characteristics is critical at the start of and throughout screening to track changes in part performance, which can be indicative of latent failure modes. The exact performance tests depend upon the device type, but examples include responsivity (photodiodes, detectors) and optical power measurements (LEDs, laser diodes).
Temperature Cycling	MIL-STD-883, Method 1010	Thermal cycling can excite failure modes related to part construction (e.g. CTE mismatches).
PIND	MIL-STD-883, Method 2020	Foreign or loose particles can interact with internal emitting, detecting, and electrical surfaces, leading to degraded performance and eventually failure.
Burn-in	MIL-STD-883, Method 1015	Generally some level of burn-in is performed by the part manufacturer at the die level, but by performing burn-in at the component level one can screen for infant mortalities caused by shipping or processes performed during component packaging.
Thermal Impedance	MIL-STD-750, Method 3101.5	This measurement helps quantify the thermal connection between a source and external packaging; it is not frequently required, but can be included at project discretion.
Hermeticity	MIL-STD-883, Method 1014 -Condition CH or B (or A as Alternate) for Fine Leak -Condition CH, B3, or C4 for Gross Leak	In cases where the component performance is dependend upon the atmosphere within the device, it is critical to maintain the expected internal environment. Furthermore if a COTS part contains an unforeseen prohibited material, maintaining hermeticity can avoid contamination of nearby components in-situ, preventing widespread system issues. Generally this test is performed near the end of screening to ensure all environmental testing that affects seal quality is already complete.
Vibration	GSFC-STD-7000 (GEVS), Section 2.4.2 Tables 2.4-3 and 2.4-4 are also referenced	The Goddard Environmental Verification Standards help provide basic guidelines for system-level and component-level vibration testing. This includes Sine-Sweep, Random, and Shock vibration testing.

Summary

- NASA GSFC has been screening and qualifying photonic/optoelectronic components for more the past 30 years.
  - Trends indicate decreasing component size, weight, and power (SWaP).
  - Screening and qualification **does not** have to be expensive and time-consuming.
  - ***Most photonic parts are COTS!*** **Non optical flight systems & parts engineers may not know this.**
- When dealing with components that have flown in **some configuration** it's up to the project **and** vendor to qualify, be honest with flight heritage, and **re-qualify when necessary**.
  - **Systems engineers** please have a comprehensive understanding of requirements trades/test plans can be made expediently to reduce cost/schedule risk.
  - **Parts engineers** may try and levy EEE parts test plans – those needs to be modified for optoelectronics.
  - **Vendors** please communicate regarding procedural changes on "heritage" parts to continue "preferred" supplier standing.
- Contracting non-profit independent test houses (NASA, institutions are examples) creates naturally secure collection points for failure modes, mechanisms, and test data.
  - Agreements similar to Space Acts (industry using NASA resources) with us allow communication without giving away proprietary information.

Thank You to our Partners!

(not all are here)

HQ, JSC, GSFC, KSC, MSFC

And thank you for your time!

https://photonics.gsfc.nasa.gov

BACK UP SLIDES

Acronyms

- ASTM = American Society for Testing and Materials
- ASU = Arizona State University
- ATLAS = Advanced Topographic Laser Altimeter System
- CATS = Cloud-Aerosol Transport System
- COTS = Commercial Off the Shelf
- DIY = Do It Yourself
- EEE = Electrical, Electronic, and Electromechanical
- FC = Field Connector
- GCD = Game Changing Development
- GEDI = Global Ecosystem Dynamics Investigation
- GEVs = Goddard Environmental Specification
- GEO = Geosynchronous Orbit
- GOES-R = Geostationary Operational Environmental Satellite-R Series
- GLAS = Geoscience Laser Altimeter System
- GSFC = Goddard Space Flight Center
- ICESat = Ice, Cloud, and land Elevation Satellite
- InP PIC = Indium-Phosphide Photonic Integrated Circuits
- ISS = International Space Station
- JWST = James Webb Space Telescope
- LADEE = Lunar Atmosphere Dust Environment Explorer
- LED = Light Emitting Diode
- LEO = Lower Earth Orbit
- LiDAR = Light Detection and Ranging
- LIV=Light-Current-Voltage
- LOLA = Lunar Orbiter Laser Altimeter
- LRO = Lunar Reconnaissance Orbiter
- MAVEN = Mars Atmosphere and Volatile Evolution Mission
- MESSENGER = Mercury Laser Altimeter on Mercury Surface, Space Environment, Geochemistry and Ranging
- MEO = Medium Earth Orbit
- MIL-STD = Military Standards
- MLA = Mercury Laser Altimeter
- MOLA = Mars Orbiter Laser Altimeter
- MOMA = Mars Organic Molecule Analyzer
- NEPP = NASA Electronic Parts and Packaging Program
- OTES = OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer) Thermal Emission Spectrometer
- PER = Polarization Extinction Ratio
- SAA = Space Act Agreement
- SM APC= Single Mode Angled Physical Contact
- SEM = Scanning Electron Microscope
- SPLICE = Space Technology Mission Directorate, Safe and Precise Landing – Integrated Capabilities Evolution Program
- SSCO = Space Servicing Capabilities Office
- SSCP = Space Servicing Capabilities Project
- SWaP = Size, Weight and Power
- TEC = Thermoelectric Cooler
- TID = Total Ionizing Dose
- TSIS = Total and Spectral Solar Irradiance Sensor
- TRL = Technical Readiness Level
- VSS = Vision Sensor Subsytem

References

1. Melanie N. Ott et al. "Optical fiber cable assembly characterization for the mercury laser altimeter", Proc. SPIE 5104, Enabling Photonic Technologies for Aerospace Applications V, (14 July 2003) https://photonics.gsfc.nasa.gov/tva/meldoc/spieavims2003.pdf
2. Dave Smith et al. “Two-Way Laser Link over Interplanetary Distance,” Science Magazine, (www.sciencemag.org) Vol. 311 (5757) January 6, 2006, pp 53. https://science.sciencemag.org/content/311/5757/53
3. Melanie N. Ott et al. "Development, qualification, and integration of the optical fiber array assemblies for the Lunar Reconnaissance Orbiter", Proc. SPIE 7095, Nanophotonics and Macrophotonics for Space Environments II, 70950P (26 August 2008). https://photonics.gsfc.nasa.gov/tva/meldoc/SPIE/2008/SPIE-MNOTT-7095-28.pdf
4. Melanie N. Ott et al. "The fiber optic system for the advanced topographic laser altimeter system instrument (ATLAS)", Proc. SPIE 9981, Planetary Defense and Space Environment Applications, 99810C (19 September 2016). https://photonics.gsfc.nasa.gov/tva/meldoc/SPIE/2016/SPIE-2016-ICESat-2-ATLAS-Fiber-System.pdf
5. C. A. Lindensmith et al. "Development and qualification of a fiber optic cable for Martian environments", Proc. SPIE 10565, International Conference on Space Optics — ICSO 2010, 1056519 (20 November 2017). https://photonics.gsfc.nasa.gov/tva/meldoc/ICSO/2010/ChemCam-Assemblies-ICSO2010.pdf
6. Melanie N. Ott. “Space Flight Requirements for Fiber Optic Components; Qualification Testing and Lessons Learned, Invited paper”, International Society for Optical Engineering, SPIE Europe Conference on Reliability of Optical Fiber Components, Devices, Systems and Networks III, Vol. 6193 (April 2006). https://photonics.gsfc.nasa.gov/tva/meldoc/spie-6193-7-MOtt.pdf
7. Melanie N. Ott. Optical Society of America Frontiers in Optics, Session on Space Qualification of Materials and Devices for Laser Remote Sensing Instruments I, Invited Tutorial (September 2007). https://photonics.gsfc.nasa.gov/tva/meldoc/OSA-07-MOTT.pdf
8. Melanie N. Ott. “Implementation and Qualification Lessons Learned for Space Flight Photonic Components”, Invited Tutorial, International Conference on Space Optics, Rhodes Greece (October 2010) https://photonics.gsfc.nasa.gov/tva/meldoc/ICSO/2010/MOTT-NASA-Prod-ICSO_2010.pdf
9. “OSIRIS-REx Instruments.” spaceflight101.Com, 2019, https://www.spaceflight101.com/osiris-rex/osiris-rex-instruments/.
10. Alessandro, Adrienne. "NASA’s Restore-L Mission to Refuel Landsat 7, Demonstrate Crosscutting Technologies." NASA’s Goddard Space Flight Center (2016), https://www.nasa.gov/feature/nasa-s-restore-l-mission-to-refuel-landsat-7-demonstrate-crosscutting-technologies/
11. “Smallsat Developers Focus on Improving Reliability.” SpaceNews.com, 8 Aug. 2018, https://spacenews.com/smallsat-developers-focus-on-improving-reliability/
12. Grush, Loren. “After Making History, NASA's Tiny Deep-Space Satellites Go Silent.” The Verge, The Verge, 6 Feb. 2019, www.theverge.com/2019/2/6/18213594/nasa-marco-cubesats-deep-space-insight-mars-mission-communications-silent.
13. Foust, Jeff. “Is the Gateway the Right Way to the Moon?” SpaceNews.com, 30 Jan. 2019, https://spacenews.com/is-the-gateway-the-right-way-to-the-moon/
14. Hughes, Mark. “Solid-State LiDAR Is Coming to an Autonomous Vehicle Near You.” All About Circuits, 20 Feb. 2018, https://www.allaboutcircuits.com/news/solid-state-LiDAR-is-coming-to-an-autonomous-vehicle-near-you/
15. Loff, Sarah. “Morpheus Prototype Uses Hazard Detection System to Land Safely in Dark.” NASA, NASA, 13 Mar. 2015, https://www.nasa.gov/content/morpheus-prototype-uses-hazard-detection-system-to-land-safely-in-dark
16. Melanie N. Ott et al, "Applications of optical fiber assemblies in harsh environments: the journey past, present, and future", Proc. SPIE 7070, Optical Technologies for Arming, Safing, Fuzing, and Firing IV, 707009 (3 September 2008). https://photonics.gsfc.nasa.gov/tva/meldoc/SPIE/2008/SPIE-MNOTT-7070-8.pdf