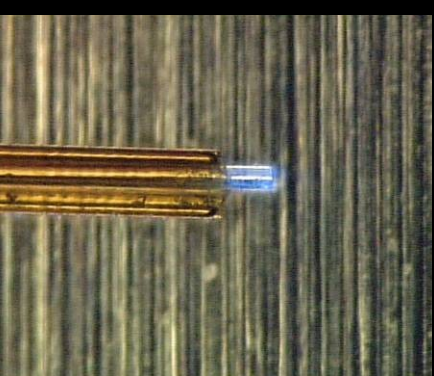
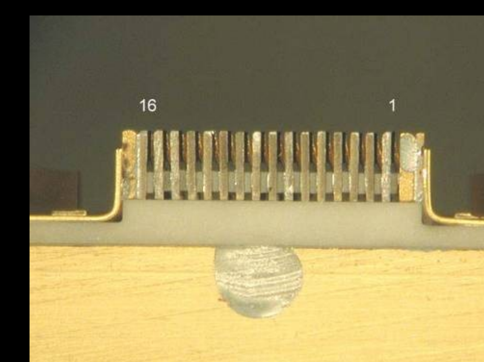
Applications of optical fiber assemblies in harsh environments, the journey past, present, and future

CODE 562 PHOTONICS Group @ GSFC

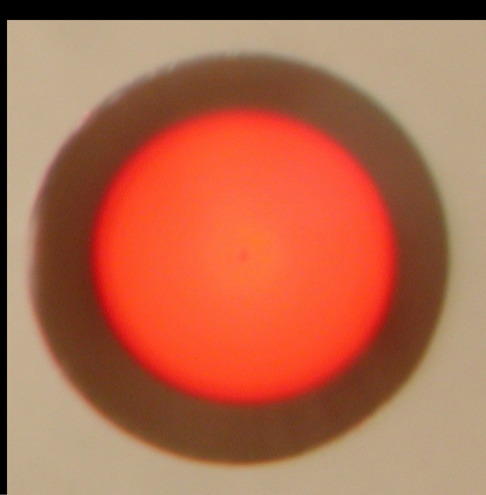


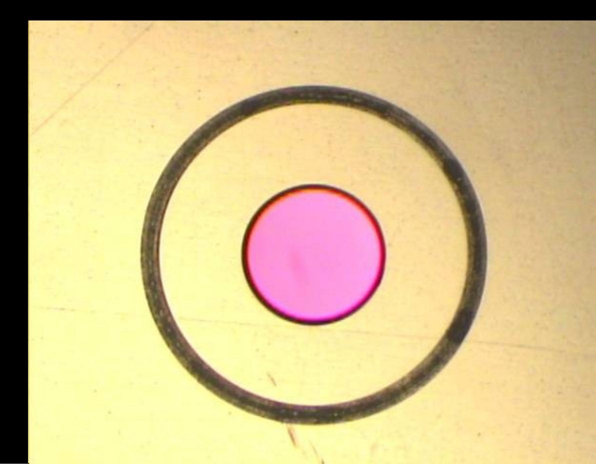


Melanie N. Ott,

NASA Goddard Space Flight Center
Applied Engineering & Technology Directorate, Electrical Engineering Division,

301-286-0127, melanie.n.ott@nasa.gov
301-286-8813, william.j.thomes@nasa.gov
misspiggy.gsfc.nasa.gov/photonics





CODE 562 PHOTONICS Group @ GSFC

Melanie N. Ott, Group Leader, 1994-2008

Applied Engineering Technologies Directorate, Electrical Engineering Division

Rob Switzer, Frank LaRocca, W. Joe Thomes, Melanie Ott, Richard Chuska

Outline

- Introductions - Who
- Successful usage of aerospace optical fiber systems – What, Where, & When.
- “Best Practices” by example – How.
- Conclusions.

A Decade of Service from the Photonics Group for Photonics & Optical Fiber Components and Assemblies Code 562, Electrical Engineering Division of AETD, NASA GSFC

Project	Dates	Design	Qualification Performance over Harsh Environment	Manufacturing	Integration	Failure Analysis
ICESAT, GLAS,	1997 - 2005	X	X	GSE		Prototype
ISS	1998 - 2008					Vendor/ Flight
ISS - HDTV	2003	X	X	FLIGHT		
Fiber Optic Data Bus	1997 -2000	X	X			
Messenger – MLA,	2001 - 2004	X	X	FLIGHT	X	
Sandia National Labs (DOE)	1998 -2008		FLIGHT			Vendor/ Flight
ISS-Express Logistics Career	2006 -2009	X	X	FLIGHT	X	
Air Force Research Lab	2003, 2008		X			
Shuttle Return To Flight	2004 -2005			FLIGHT		
Lunar Orbiter Laser Altimeter	2003 -2008	X	X	FLIGHT	X	Prototype
Mars Science Lab ChemCam	2005 -2008	X	X	FLIGHT	X	Vendor
Laser Ranging, LRO	2005 - 2008	X	X	FLIGHT	X	Prototype
Fiber Laser IIP/IRAD	2003 - 2006	X	X	QUAL		
ESA/NASA SpaceFibre	2008 (TBD)		X	QUAL		

Upcoming is the 3rd Event in coordination with ESA/CNES/JAXA/NASA on optics for space
Publications from work noted above can be found @ **misspiggy.gsfc.nasa.gov/photonics**

What? Where? When?

Historical Overview of Fiber Optics in Space 1978 - 1999

- **1978-1980, Long Duration Exposure Facility (LDEF)**
  - Passive optical fibers and fiber links

- **1989, Cosmic Background Enplorer (COBE) satellite**
  (P.I. Nobel Prize for Physics – GSFC's Dr. John Mather)
  - Used photodiodes and optical fibers in a position and motion sensing of a mirror
  - Several erroneous position determinations observed
  - Little mission impact

- **1993, Photonic Space Experiment (Boeing)**
  - Optical Fiber Radiation Experiment
  - Passive Components Experiment
  - Strained quantum well laser and custom boardband LED experiments
  - Bit Error Rate experiment

IEEE Aerospace Conference, Volume: 4 , 1998, Page(s): 421-434, MSFC 1999 Presentation

Current Fiber Data Links
(based on 1999 survey presentation)

PROJECT	LAUNCH	TECHNOLOGY	SYSTEM WAVE LENGTH
SAMPEX	7/92	MIL-STD-1773 1Mbps	850nm
MPTB	12/97	AS1773 20Mbps	1300nm
MAP	2000	AS1773 20Mbps	1300nm
XTE	12/96	MIL-STD-1773 1Mbps	850nm
HST	02/97	MIL-STD-1773 1Mbps	850nm
PSE	Proprietary	MIL- STD-1773 1Mbps	850nm
TRMM, et al.	11/97	MIL- STD-1773 1Mbps	850nm

IEEE Aerospace Conference, Volume: 4 , 1998, Page(s): 421-434, MSFC 1999 Presentation

Small Explorers (SMEX)

- SAMPEX four instruments, launched 1992 with a 1 Mbps MIL-STD-1773 Optical Fiber Databus.
- Transceivers fabricated by SCI
  - TI photonics parts.
- http://sunland.gsfc.nasa.gov/smex/sampex/
- Still functioning, last reaction wheel lost a few months ago, space craft still functioning.
- Power positive, spinning but functional for science data.
- First solid state recorder flown.

Hubble Space Telescope

- Solid state recorder UTMC protocol chips,
- Boeing transceivers. FO-1773
- Cooprocessor, SM2, 1993
- Servicing, 1995 -1997
- Still functional.

Space Borne Fiber Optic Data Bus

- Parallel Fiber Optic Data Bus, 1393
- ONI (Optivision) later became Space Photonics.
- First flight EO-1, cancelled during integration for funding issues, other instrument over budget.
- MTP Connector – Parallel
- Sandia now using optical fiber assemblies due to qualification of these assemblies during GSFC program.

Instruments & Communications (since 1999)

- **International Space Station, US LAB 2001**
  - Sent with cracked fiber, half being used, working.
  - GSFC lead failure analysis found during integration
  - Rocket engine defects are screened for and replaced during integration where possible.
- **Geoscience Laser Altimeter on ICESAT** (2003 launch)
  - Multi and single mode fibers, AVIM,
  - 2 Km of fiber used for delay line.
  - Confirms global warming
- **Mercury Laser Altimeter**, (2004 launch)
  - Receiver optic System(AVIM, Flexlite, Multimode Fiber)
  - Longest laser link established through space 24 MKm
  - Currently sending data from Mercury.

Instruments & Communications (1999 - 2008)

- **Shuttle-Return-to-Flight**
  - NEPTEC high definition laser sensor camera
  - Optical fiber assemblies for laser and receiver optics
  - Terminated @ GSFC,
  - Packaging and failure analysis support for individual vendors.
- **GLAST**, using wavelength shifting fibers (launched 6-11-08)
- **Laser Ranging and Lunar Orbiter Laser Altimeter** (LRO launch 11-08)
  - Array bundles as part of receiver optical systems
  - LR Assemblies 10 m of 7 fiber bundles across 3 subsystems.
- **Express Logistics Carrier interface to ISS (ELC)**
  - (smart warehouse)
  - Space Photonics Transceivers, In house Electronics
  - In house manufacturing of Optical Fiber Harnessing.

Military Use of Optical Fiber Systems

- Several Classified DoD Spacecraft with 10+ year operational lifetimes

- Common use in military aircraft with vibration and thermal environments that far exceeds space craft environmental requirements.

F-16 E/ F

F-18

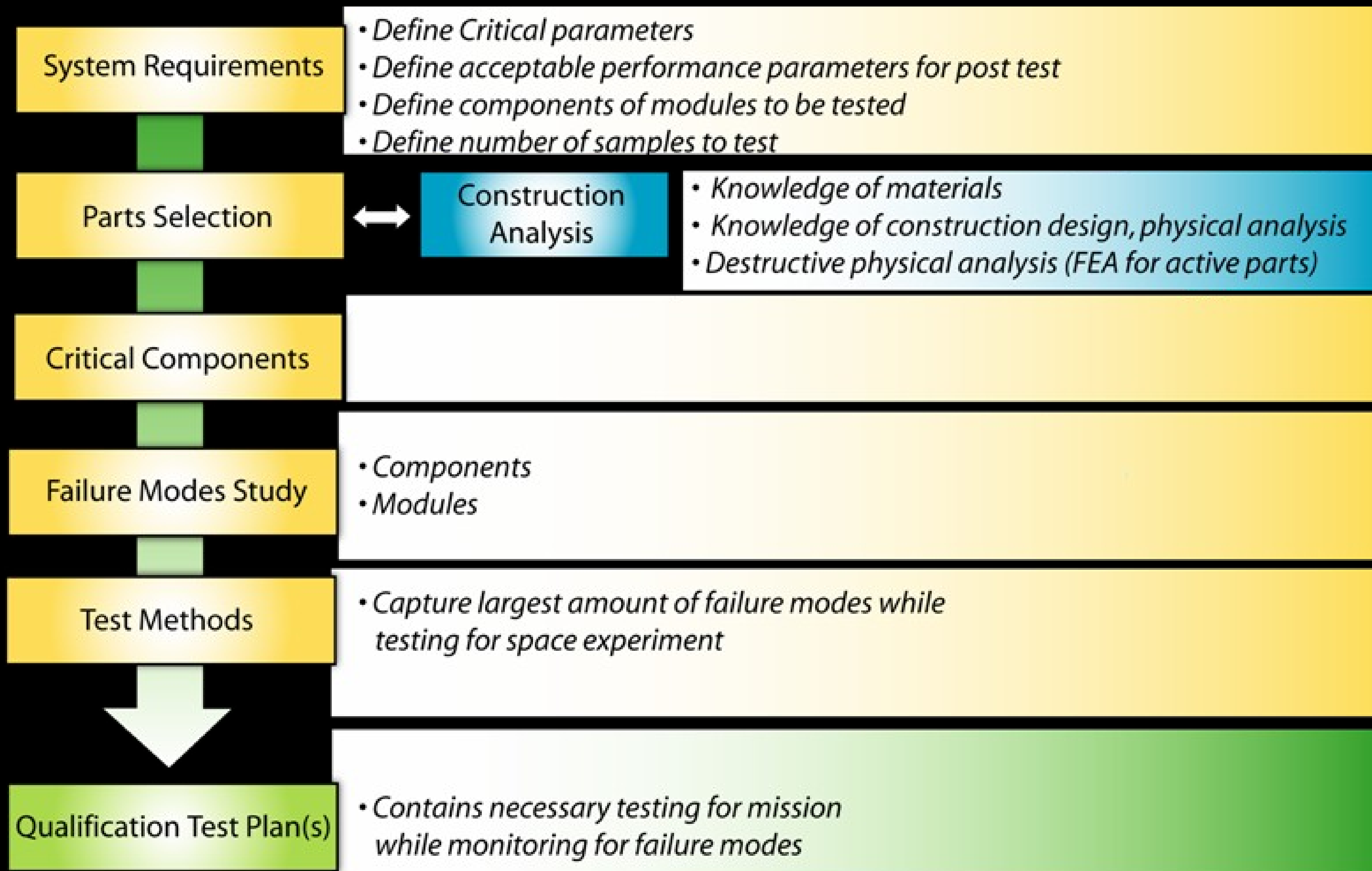
B2

F-22

F-35

How?

COTS Technology Assurance Approach



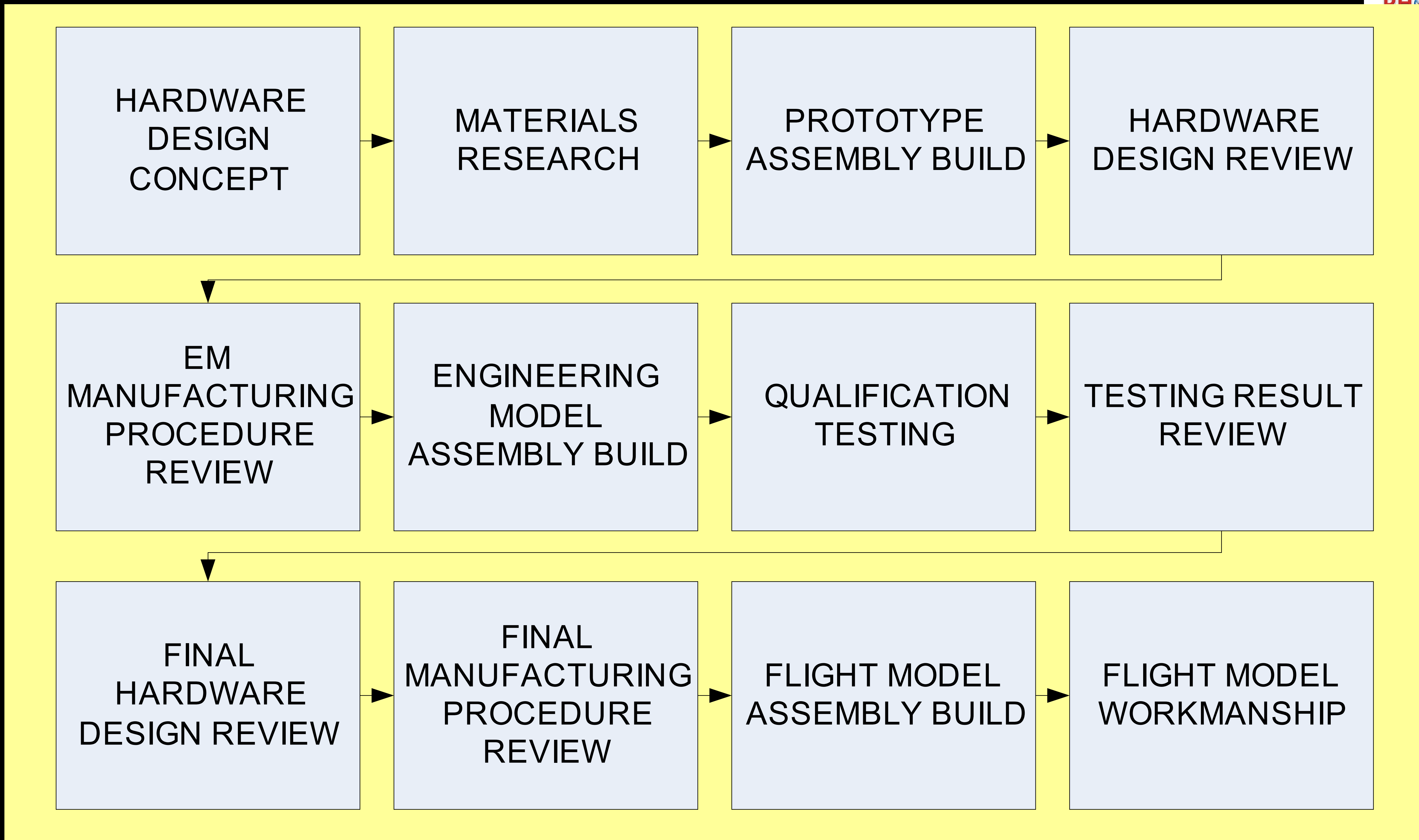
* *Photonic Components for Space Systems*, M. Ott, Presentation for Advanced Microelectronics and Photonics for Satellites Conference, 23 June 2004.

COTS Space Flight "Qualification"

Materials Analysis	• Outgas testing for anything unknown • Take configuration into account
Vibration Survival and "Shock Test"	• Use components levels as defined by system requirements • Define parameters to monitor during testing
Thermal Cycling / Aging Test	• Define which parameters will indicate which failure mode • Monitor those parameters during testing
Radiation Testing	• Acclerated dose rate • Extrapolation model use if possible • Worst conditions
Additional Tests	• Based on specific mission requirements
Qualification Assurance Plan	• Continued reliable performance over life of mission

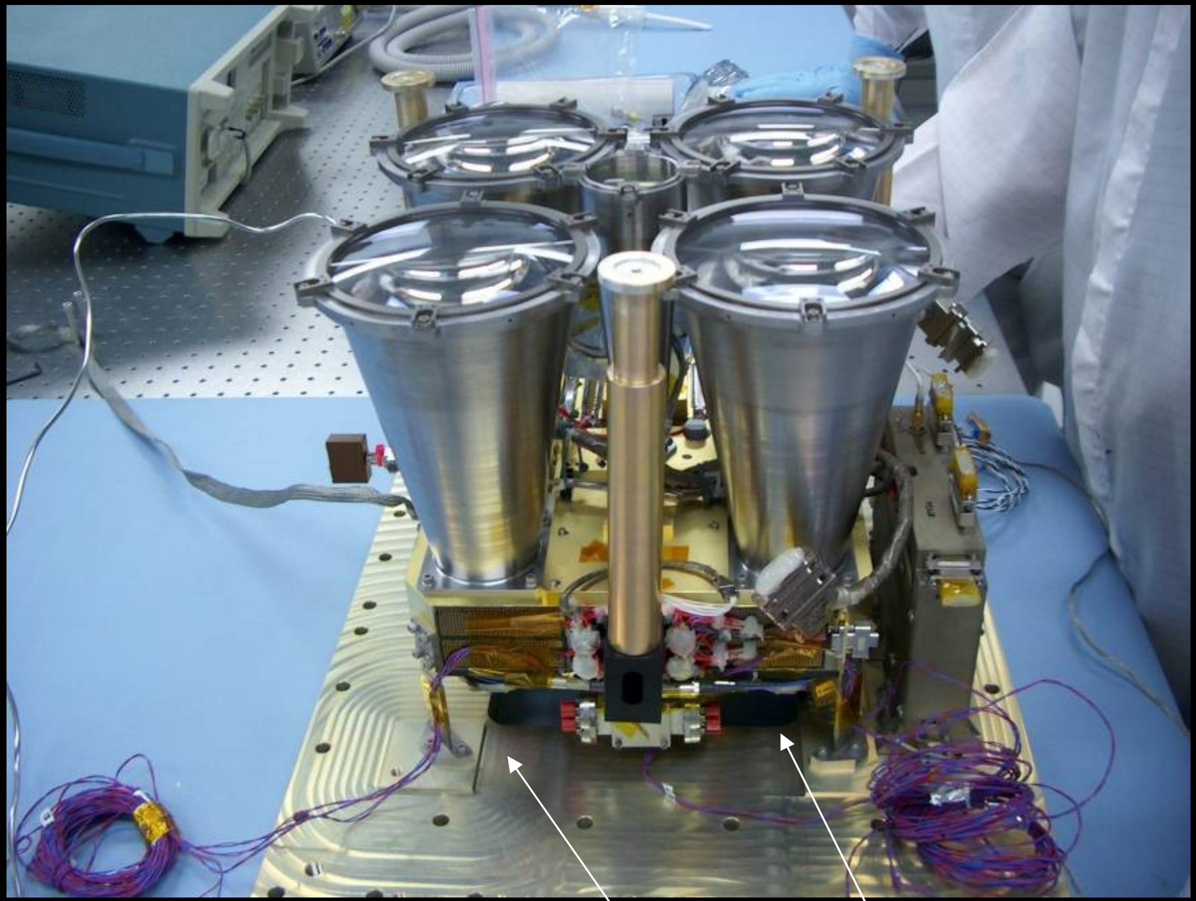
* *Photonic Components for Space Systems*, M. Ott, Presentation for Advanced Microelectronics and Photonics for Satellites Conference, 23 June 2004.

How Does the Photonics Group Go from Ideas to Flight?



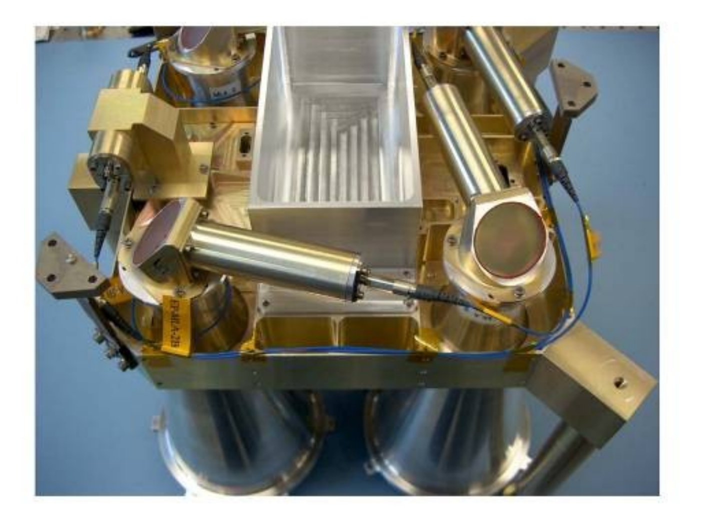
BASIC PRODUCT LIFE CYCLE

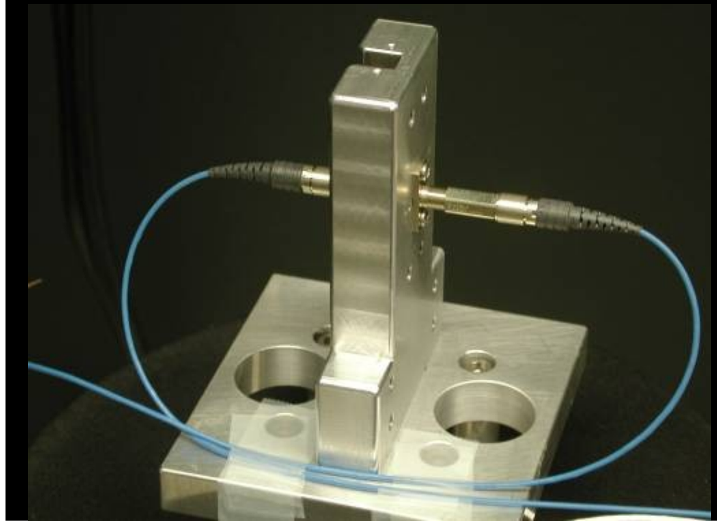
Mercury Laser Altimeter 2001-2003



Receiver telescopes focused into optical fiber assemblies that route to different detectors.

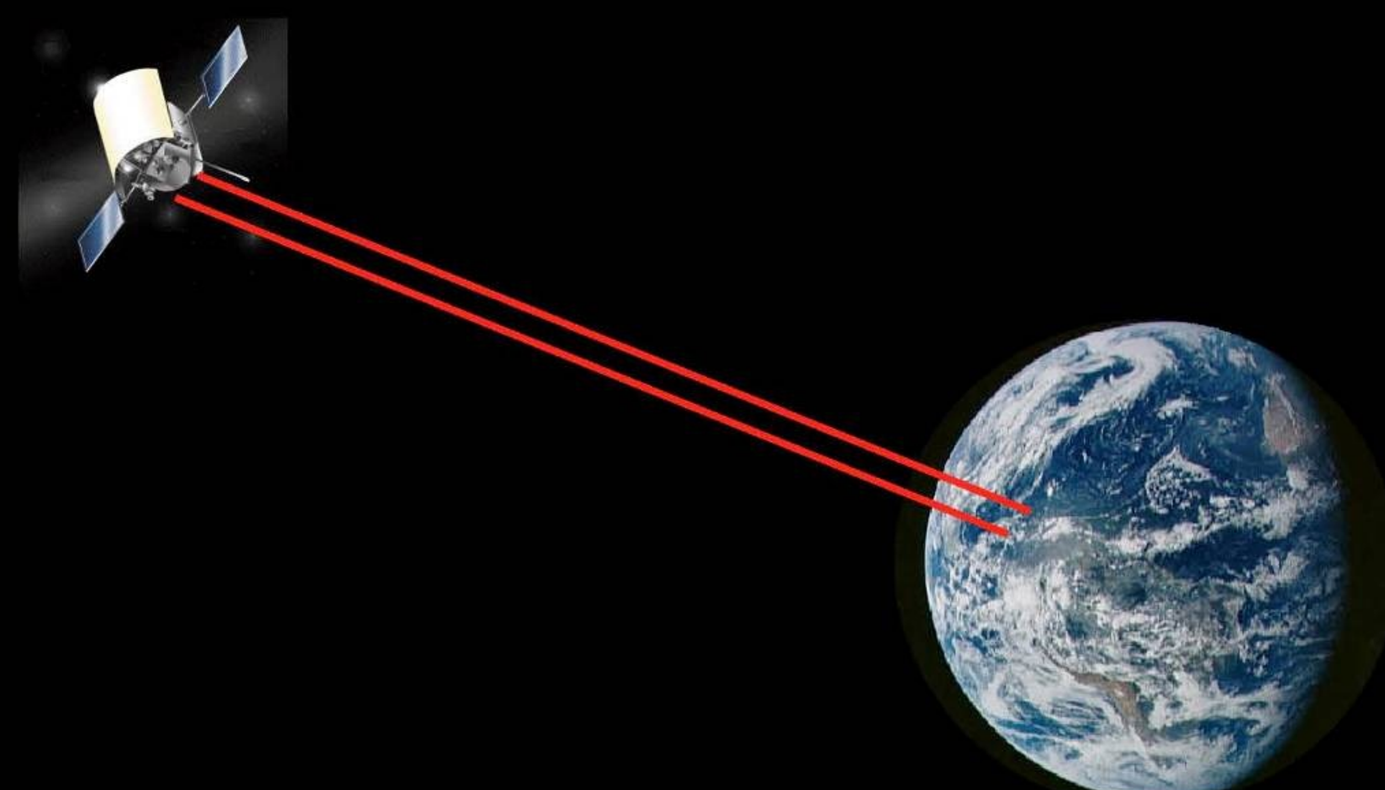
The MLA is aboard MESSENGER on its way to Mercury!





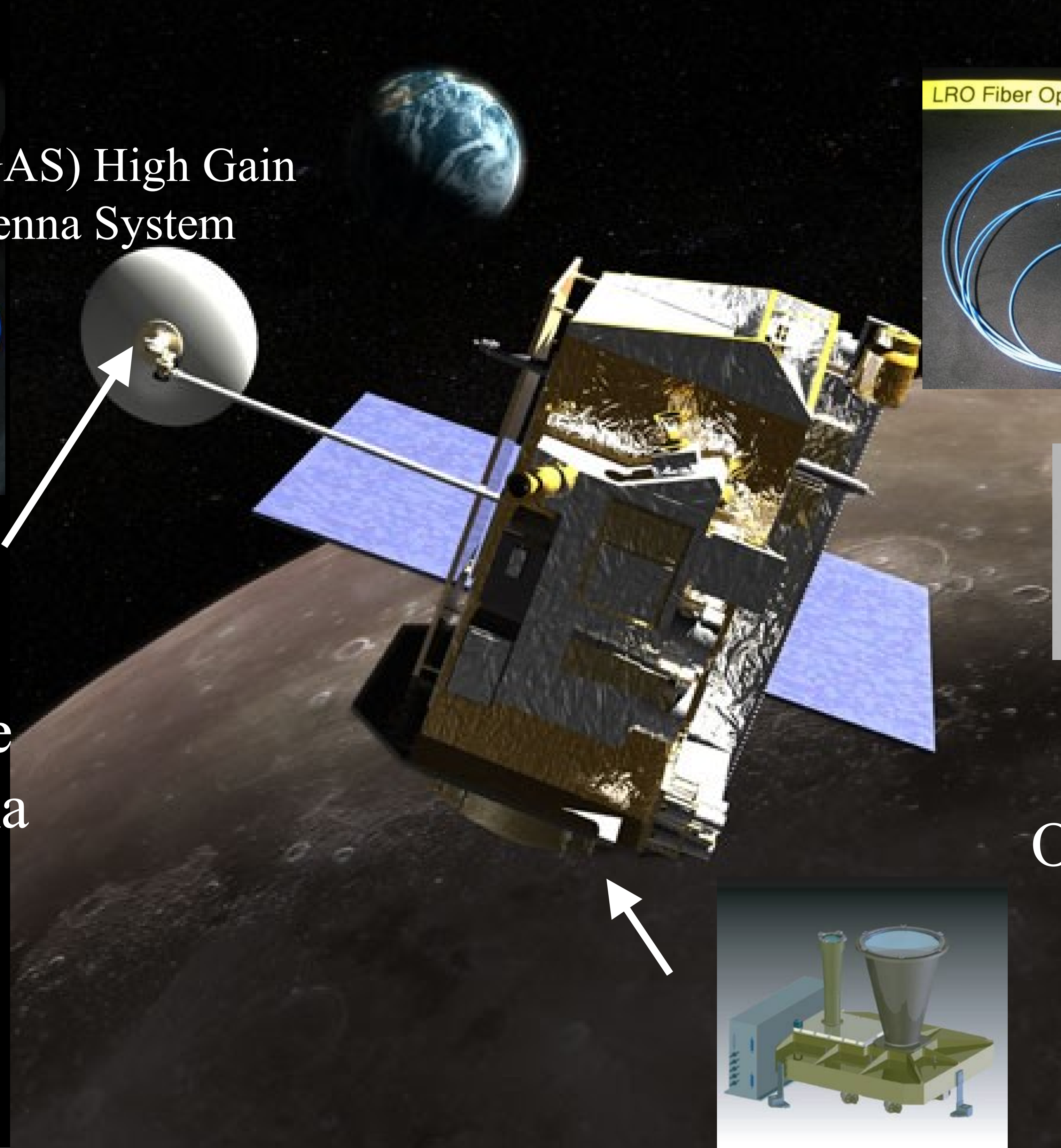
The 24 Million Km Link with the Mercury Laser Altimeter

Jay Steigelman
Dave Skillman
Barry Coyle
John F. Cavanaugh
Jan F. McGarry
Gregory A. Neumann
Xiaoli Sun
Thomas W. Zagwodzki
Dave Smith
Maria Zuber

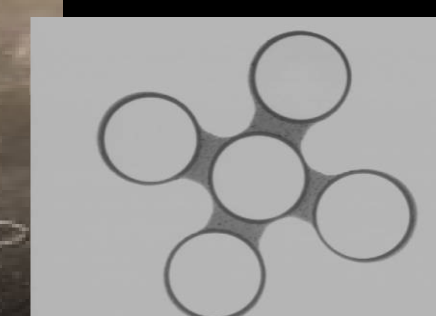


MOLA Science Team Meeting
Bishop's Lodge, Santa Fe, NM
August 24-25, 2005

The Lunar Reconnaissance Orbiter; The Laser Ranging Mission and the Lunar Orbiter Laser Altimeter



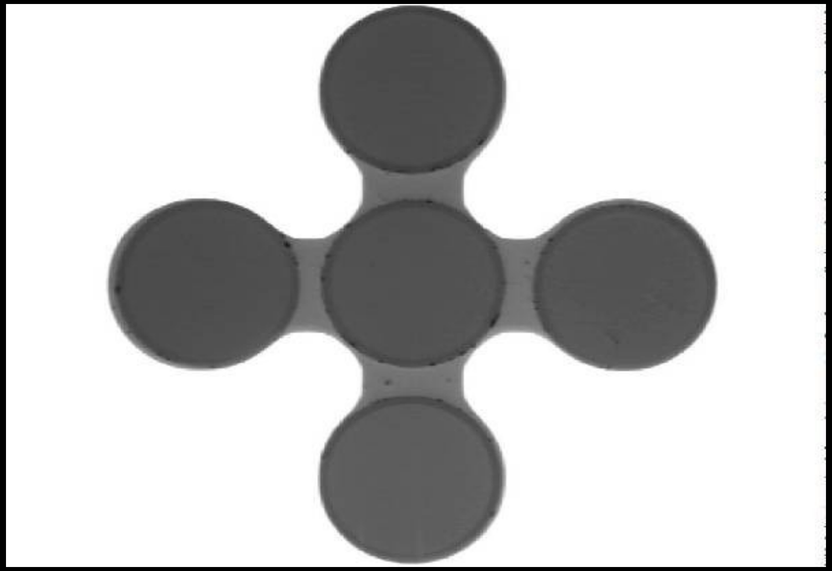
(HGAS) High Gain Antenna System



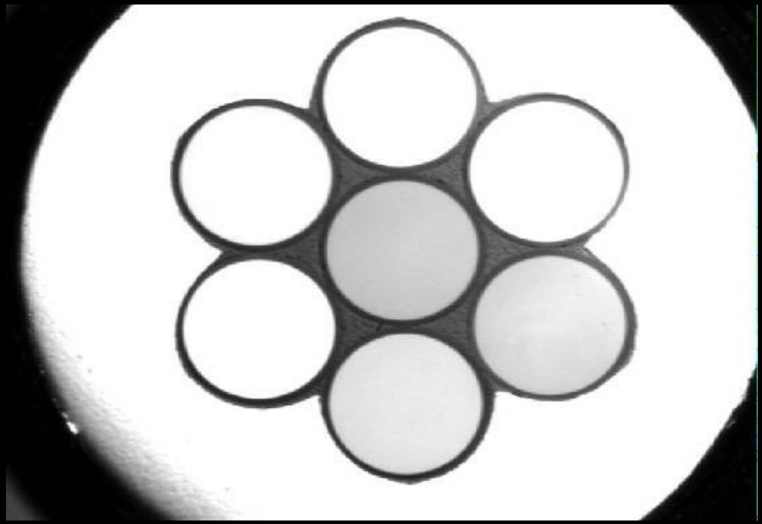
Receiver Telescope mounted on antenna and a fiber array to route signal from HGAS to LOLA

Lunar Orbiter Laser Altimeter (LOLA)

NASA GSFC Fiber Optic Array Assemblies for the Lunar Reconnaissance Orbiter



Array Side End Face Picture at 200X magnification



End Face Picture of both assembly ends at 200X magnification

Lunar Orbiter Laser Altimeter (LOLA) Assemblies
Description: 5 Fiber Array in AVIM PM on Side A, Fan out to 5 individual AVIM connectors Side B
Wavelength: 1064 nm
Quantity ~ 3 Assemblies Max ~ 0.5 m long

Laser Ranging (LR) for LRO Assemblies
Description: 7 Fiber Array on both Sides in AVIM PM Connector
Wavelength: 532 nm
Quantity ~ 9 Assemblies ~ 1 to 4 m long each

LOLA Assembly Flight Flow

CABLE INSPECTION → CABLE AND BOOT PRE-CONDITIONING → MANUFACTURING → VISUAL CLOCKING

→ INSERTION LOSS TESTING → THERMAL VACUUM WORKMANSHIP → POST-VAC INSERTION LOSS TESTING → CUSTOM ADAPTER MATING

→ OPTICAL PERFORMANCE TESTING → THERMAL SURVIVAL TESTING → WORKMANSHIP VIBRATION TESTING → OPTICAL PERFORMANCE TESTING

→ AR COATING → POST AR OPTICAL PERFORMANCE → IPA RINSE → READY FOR LOLA INTEGRATION

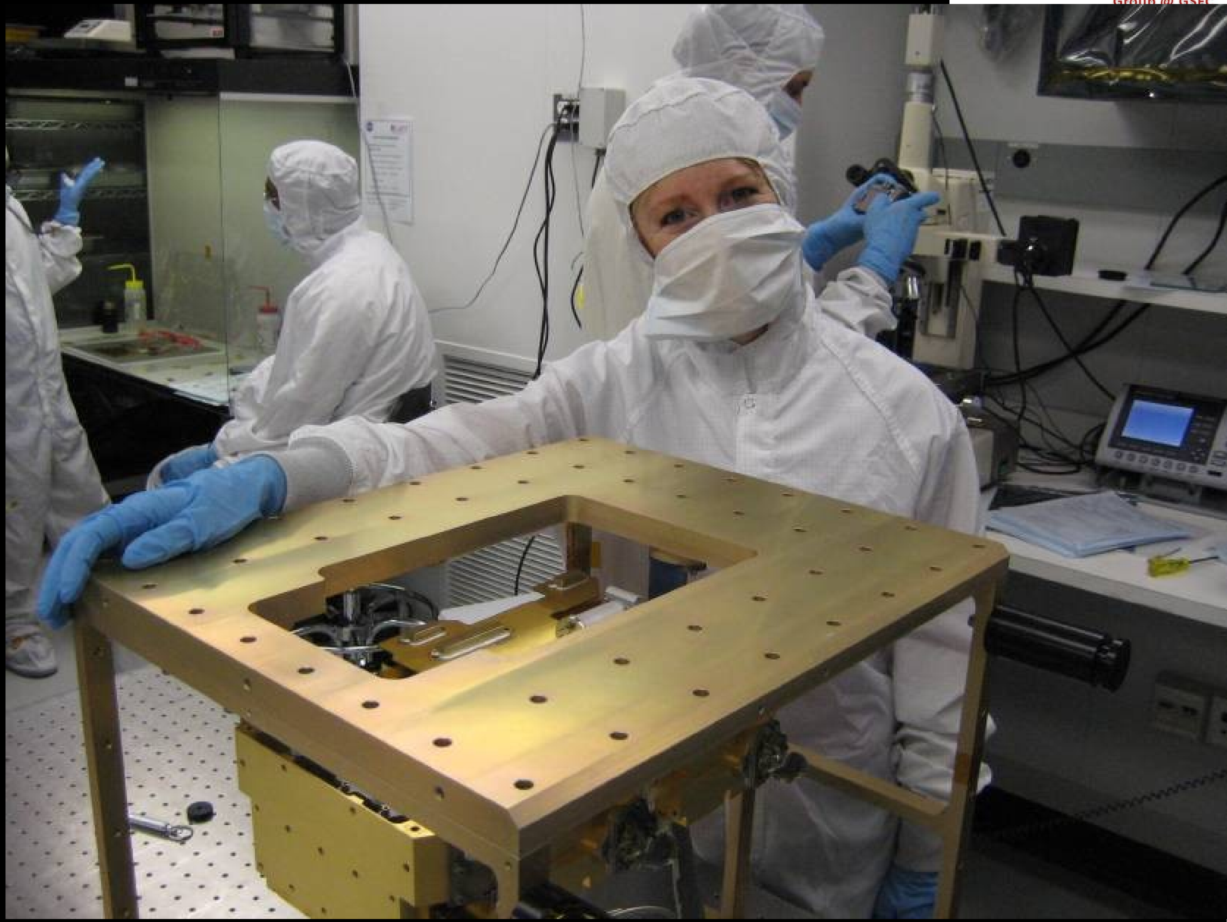
LOLA Documentation for Configuration Management

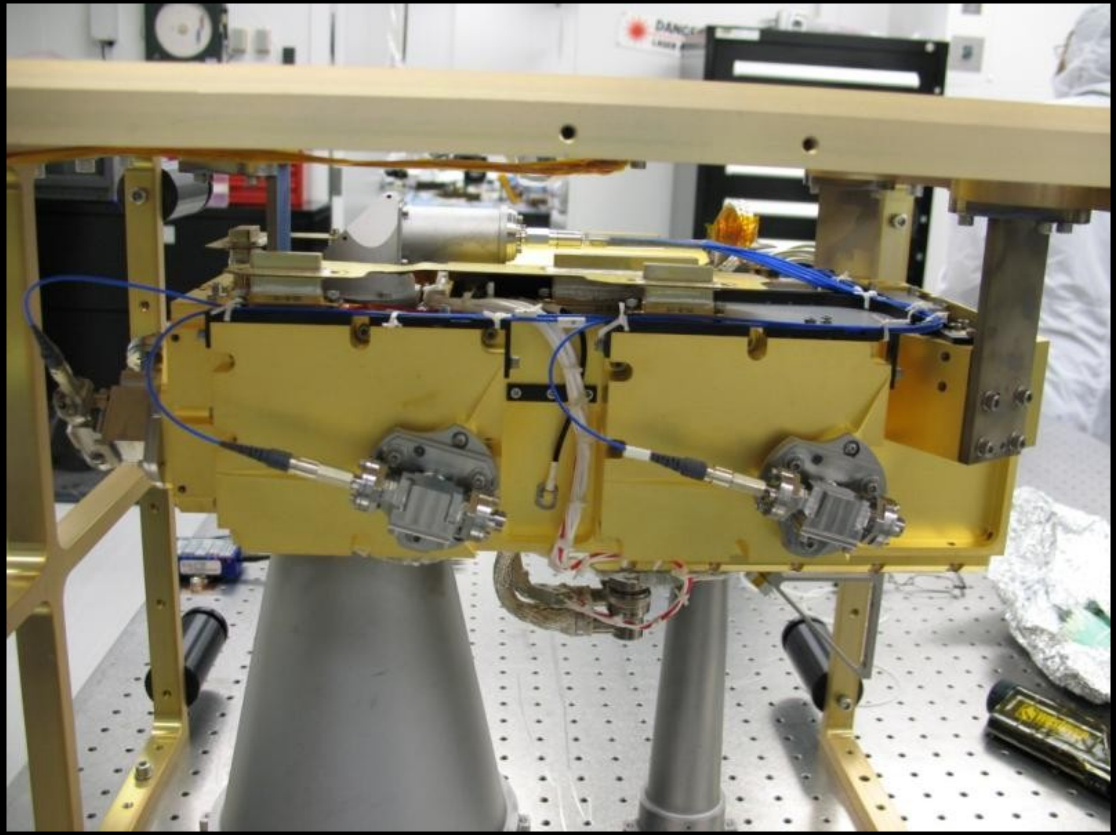
Document Name	CM Documentation Number
LOLA Fiber Optic Flight Assemblies	LOLA-OPTICS-WOA-0338
Thermal pre-conditioning on Flexlite 200/220 µm fibers for flight application	562-PHOT-WI-LOLA-TP-001
Preconditioning Procedure for AVIM Hytrel Boots for LOLA fiber optic assemblies	562-PHOT-WI-LOLA-VAC-001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

Laser Ranging on Lunar Recon Orbiter 2006-2008

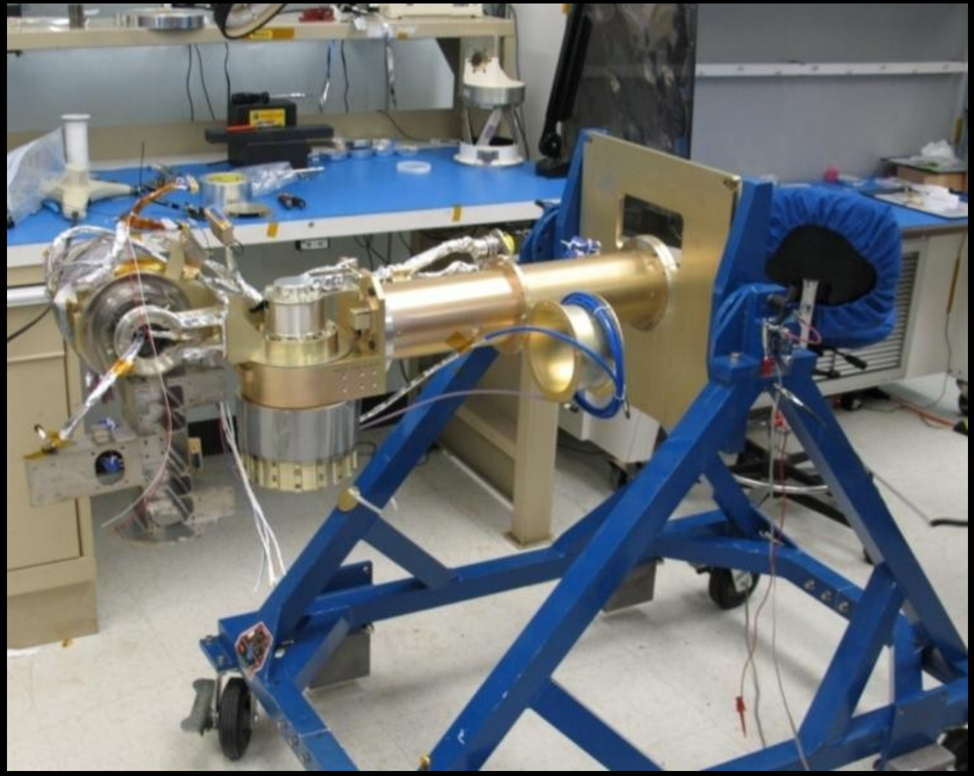
Document Name	CM Documentation Number
Thermal Pre-conditioning on Flexlite 200/220 µm fibers for flight application	LOLA-PROC-0137
Preconditioning Procedure for AVIM Hytrel Boots for LOLA fiber optic assemblies	LOLA-PROC-0138
Diamond AVIM PM Kit Pre-Assembly Inspection	LOLA-PROC-0104
Ferrule Polishing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

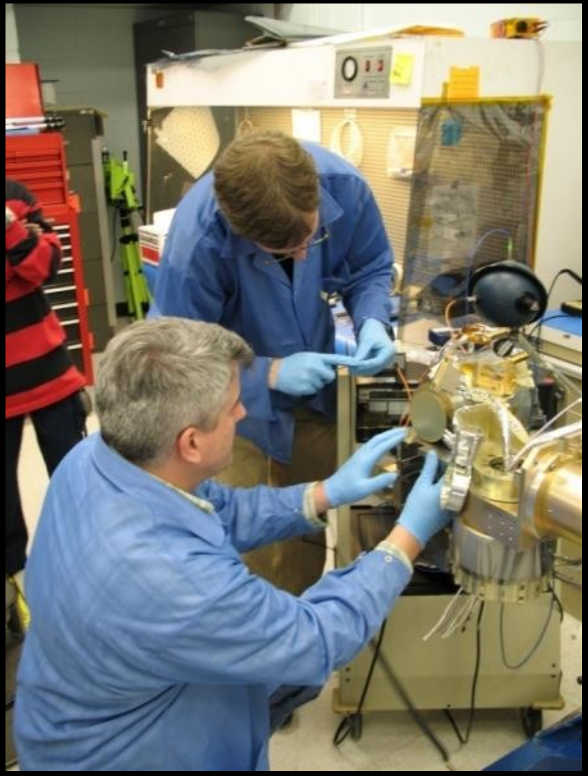
LOLA Integration, October 2007





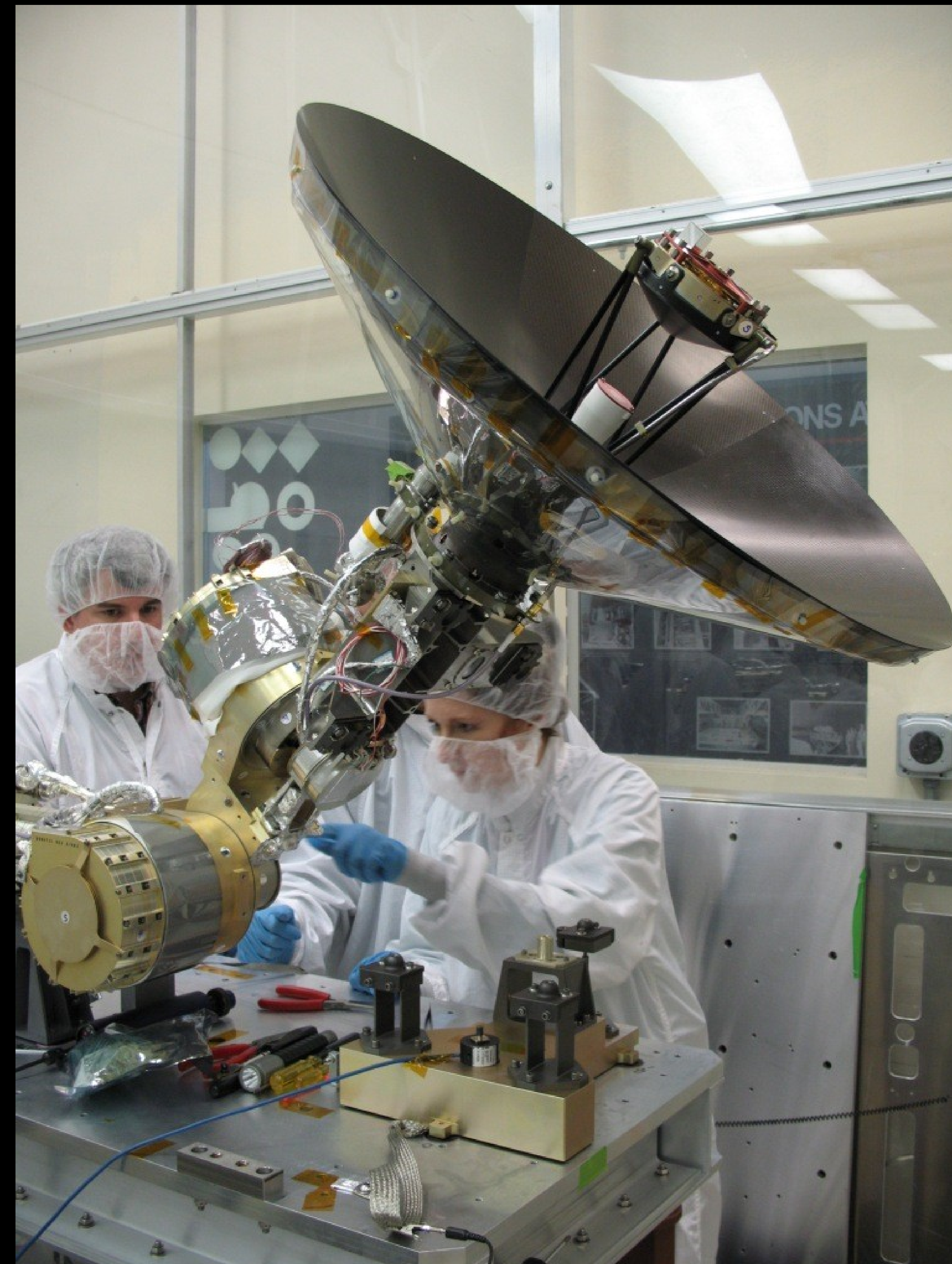
Gimbal Integration, December 2007



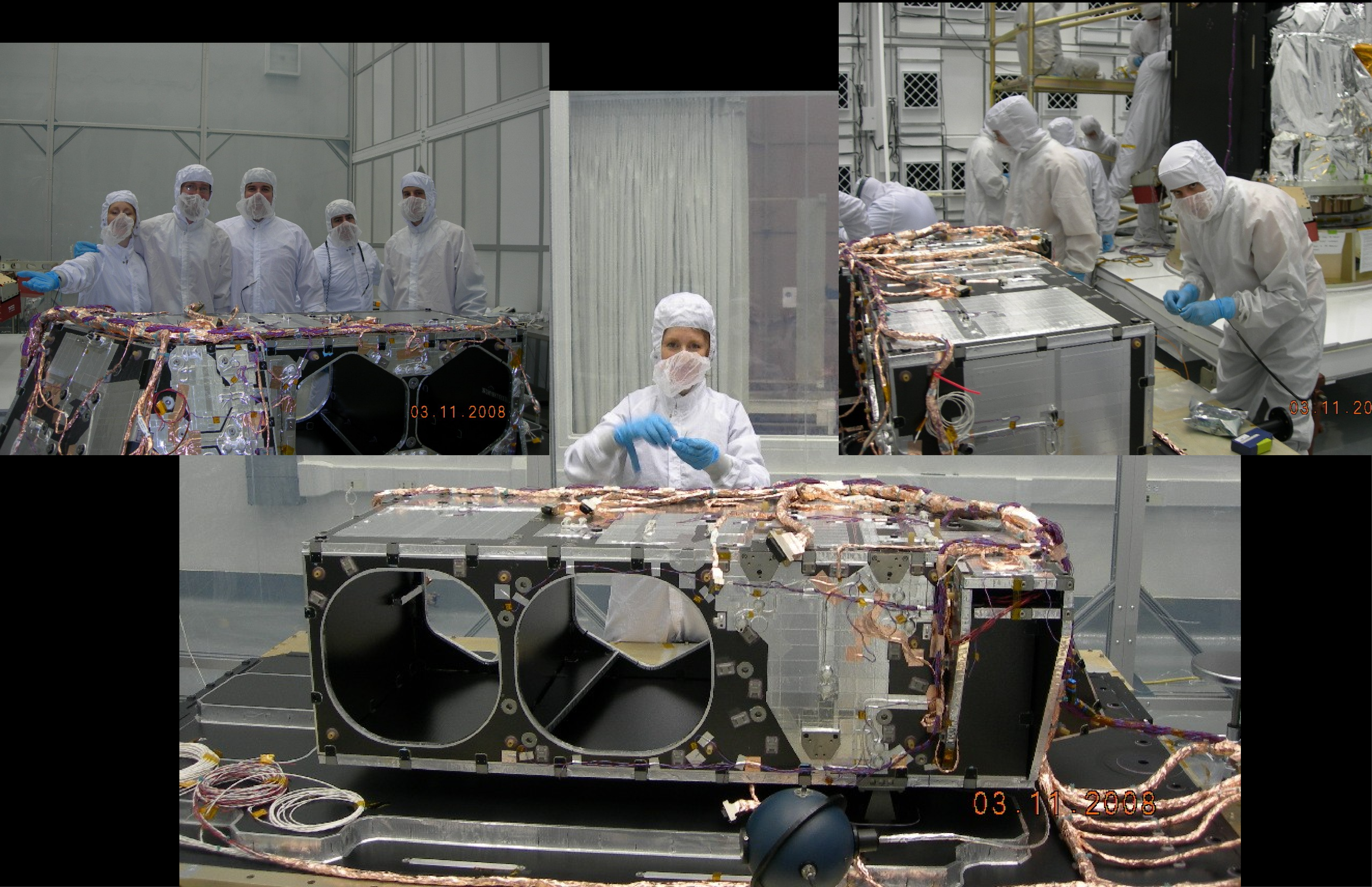


LRO Integration HGAS, 02-2008

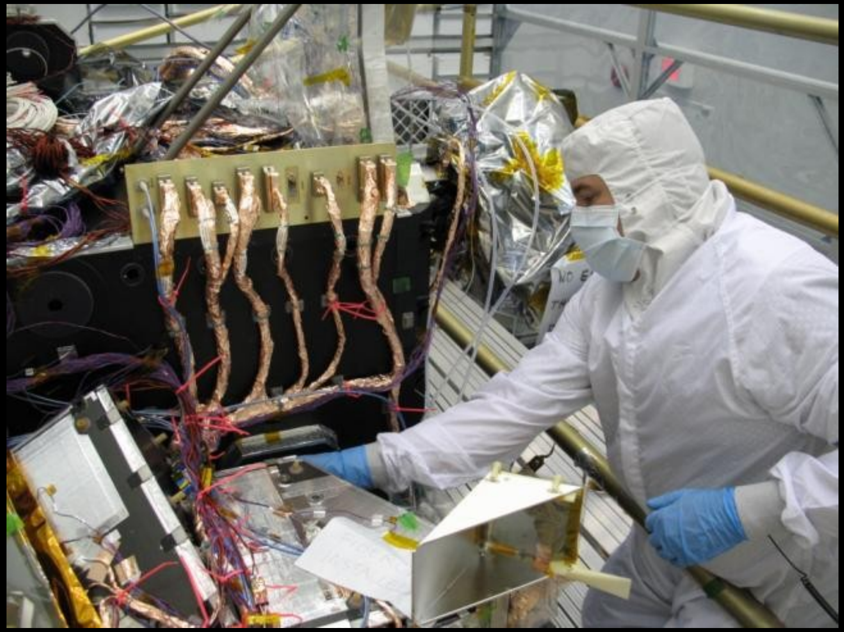
Lunar Recon. Orbiter - LRT & HGAS, 02-2008

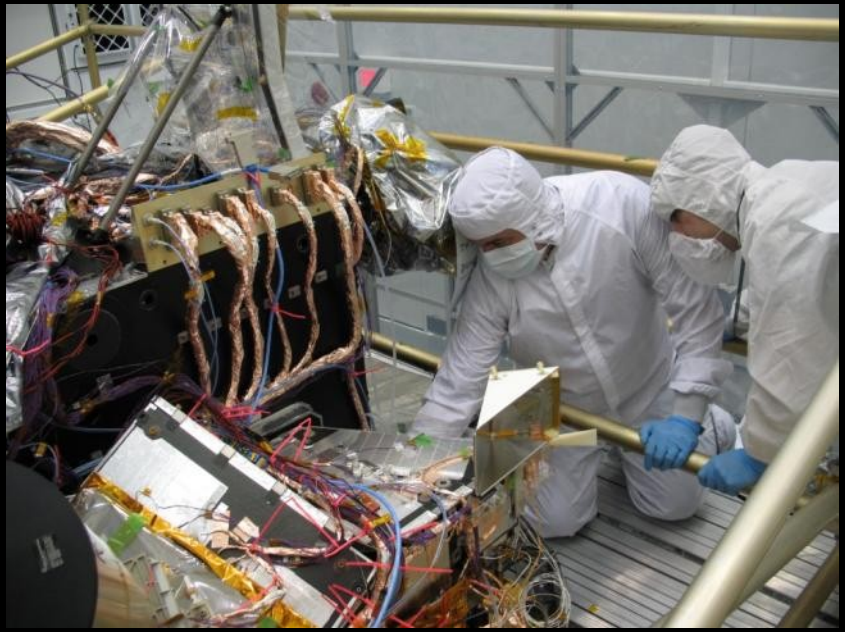


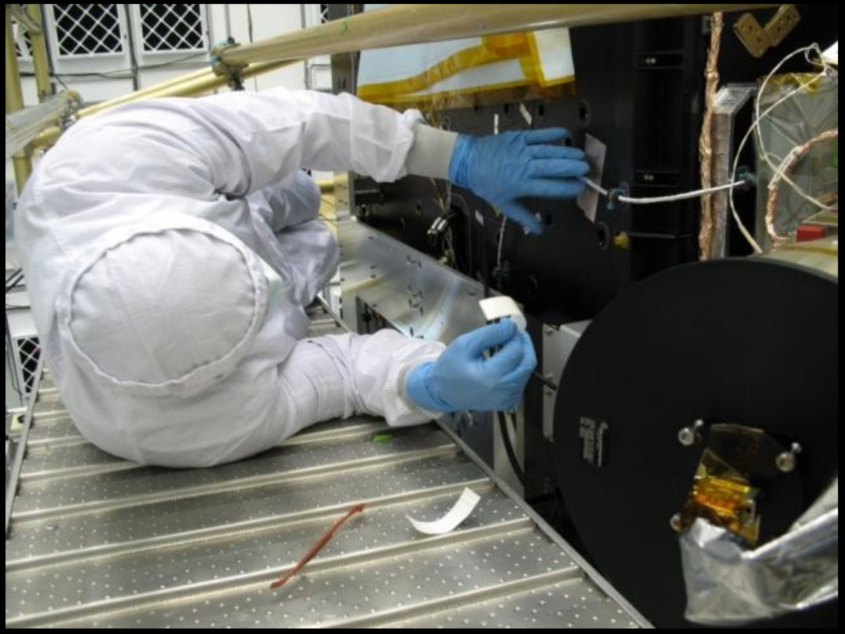
LRO Integration @ IM Deck, 03-2008



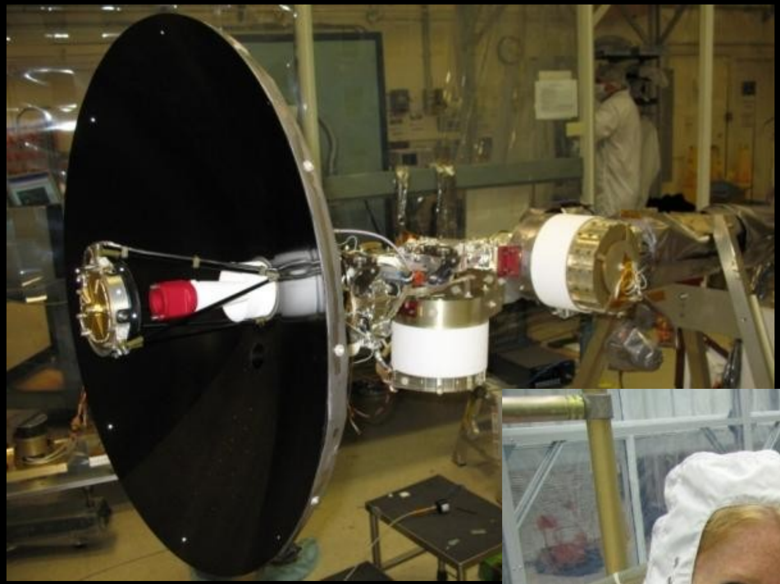
LR Segment 3 Flight Routing, April 2008

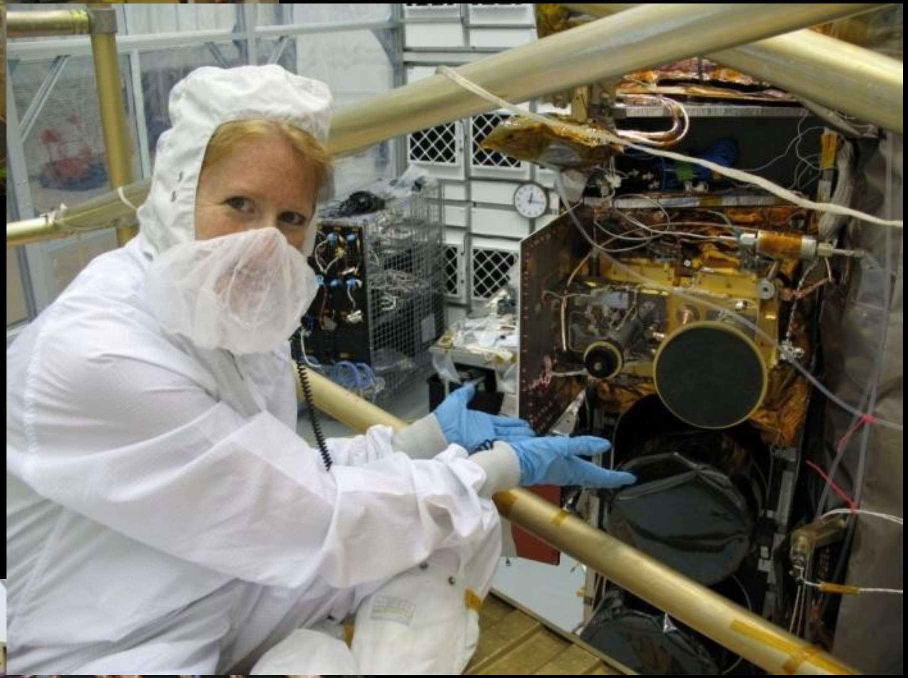


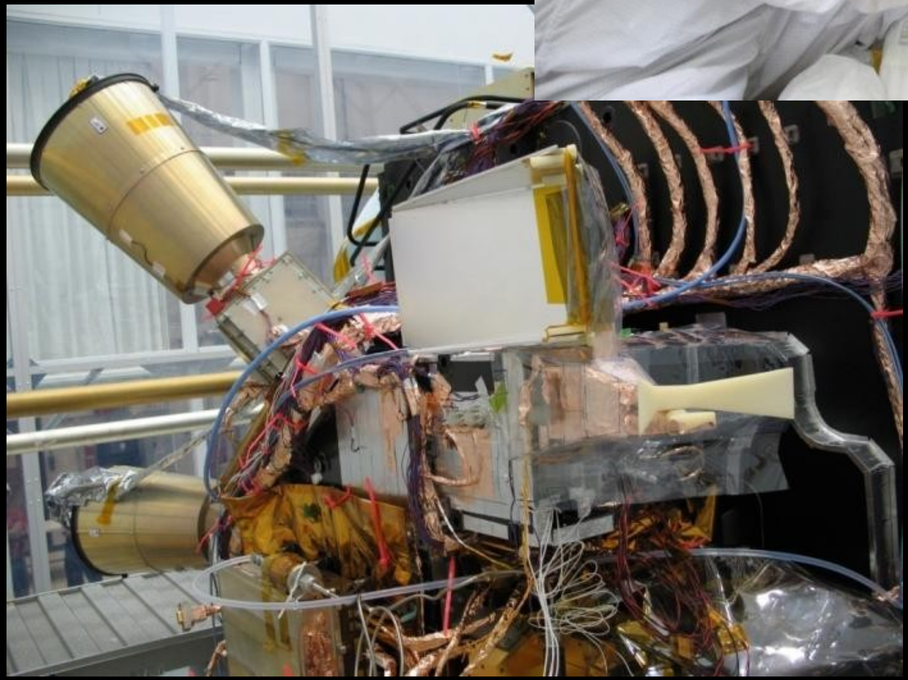


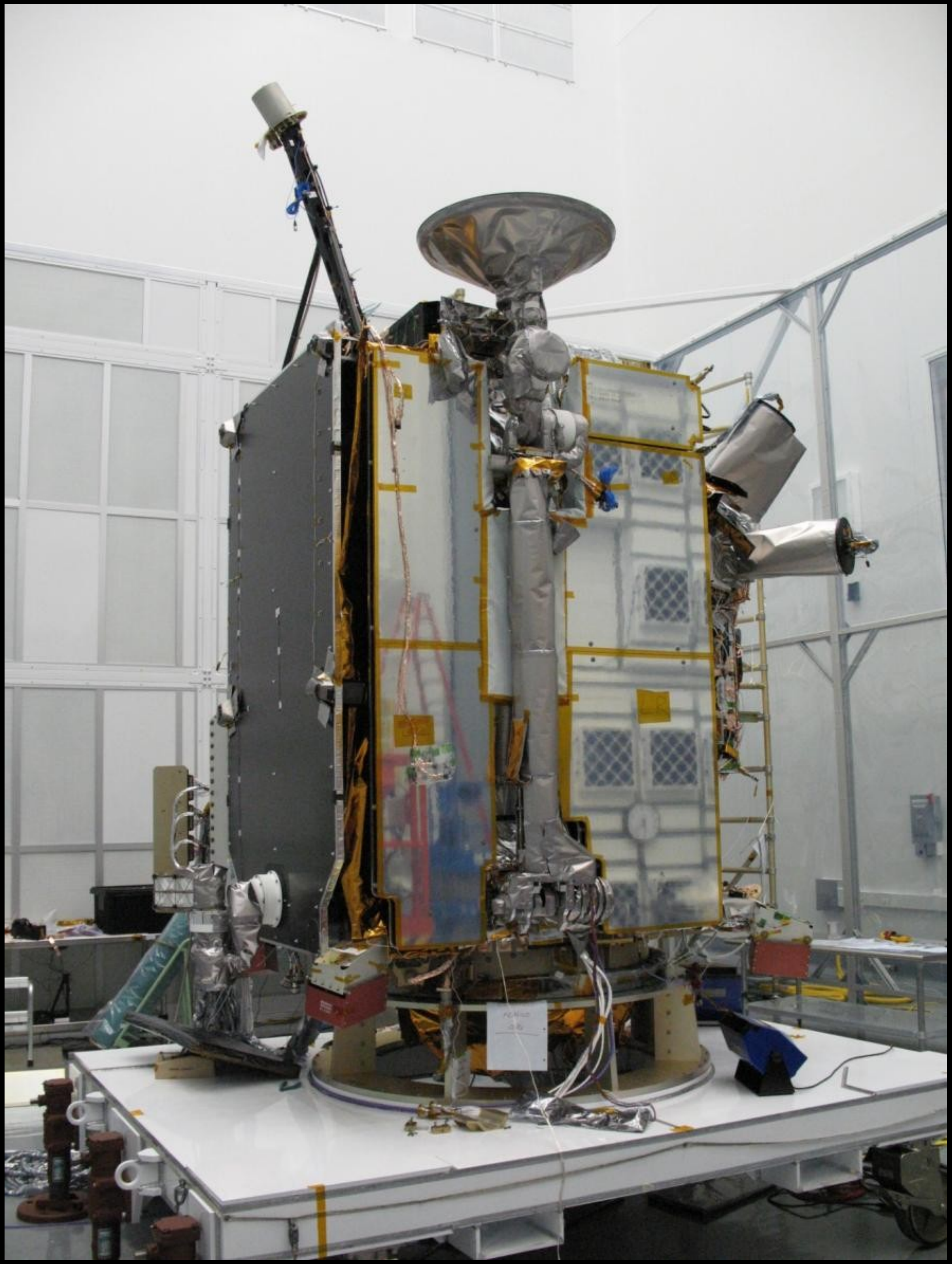


Additional Pictures of LRO, June 2008
Integration Complete

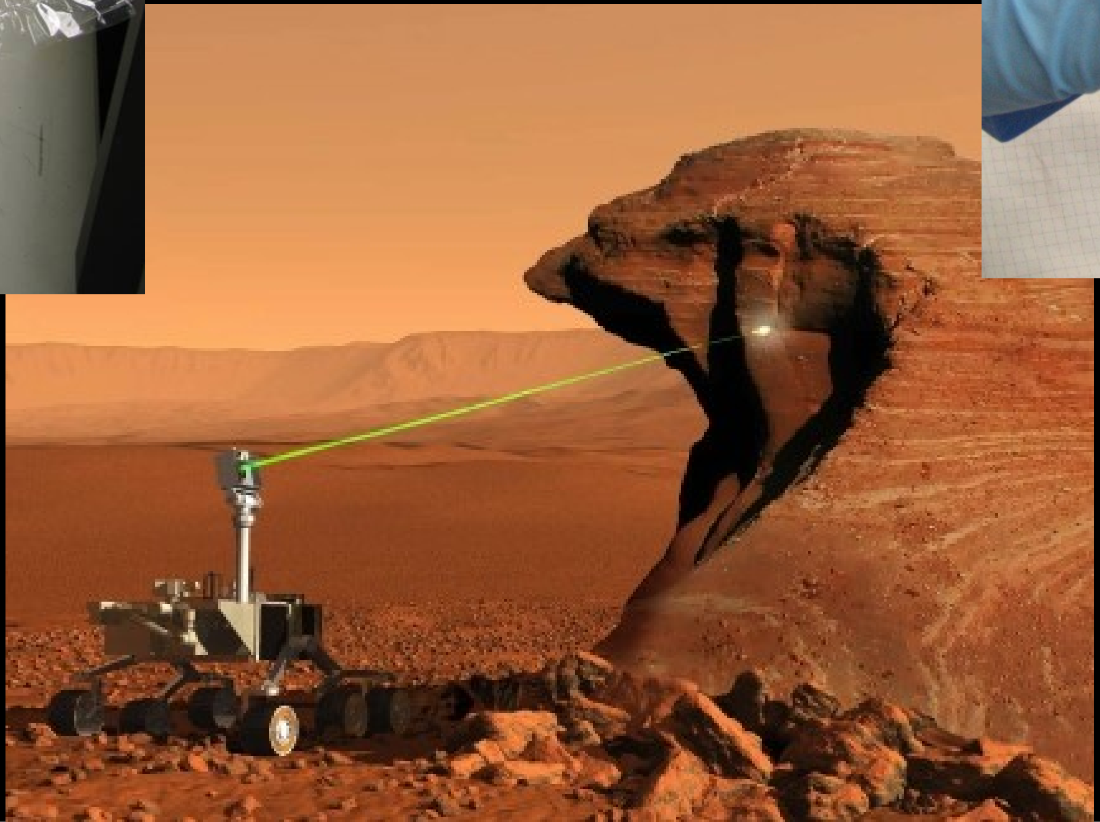








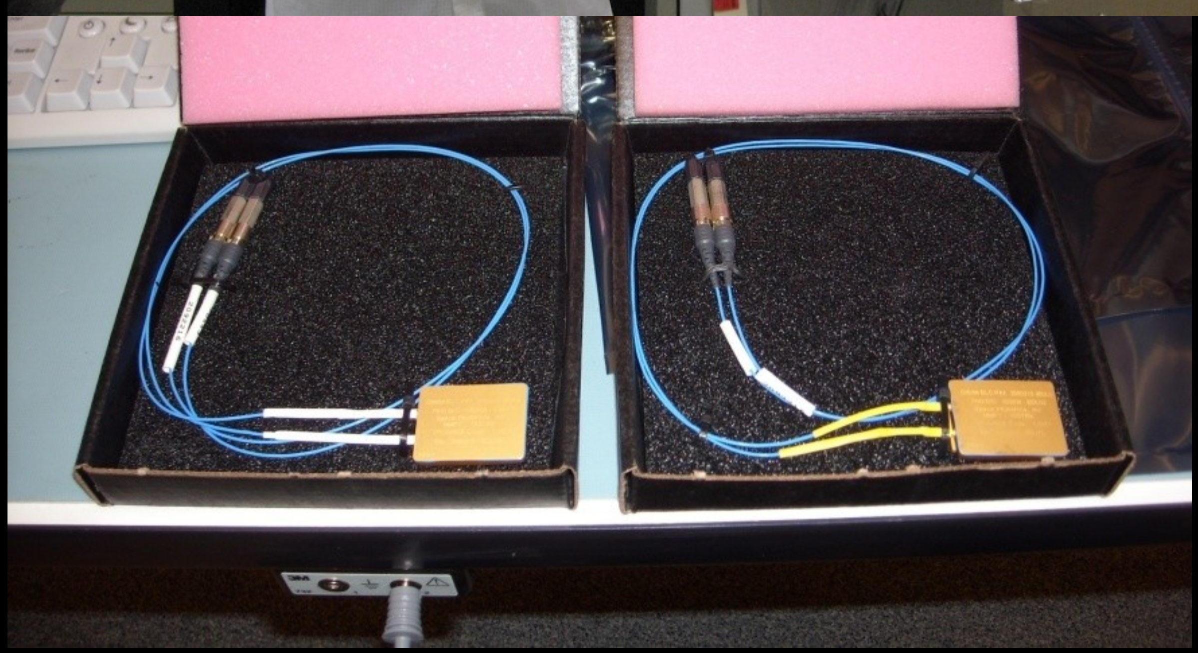
Mars Science Lab, Chem Cam
AVIM connectors – Flexlite Cable



MSL CM Documentation

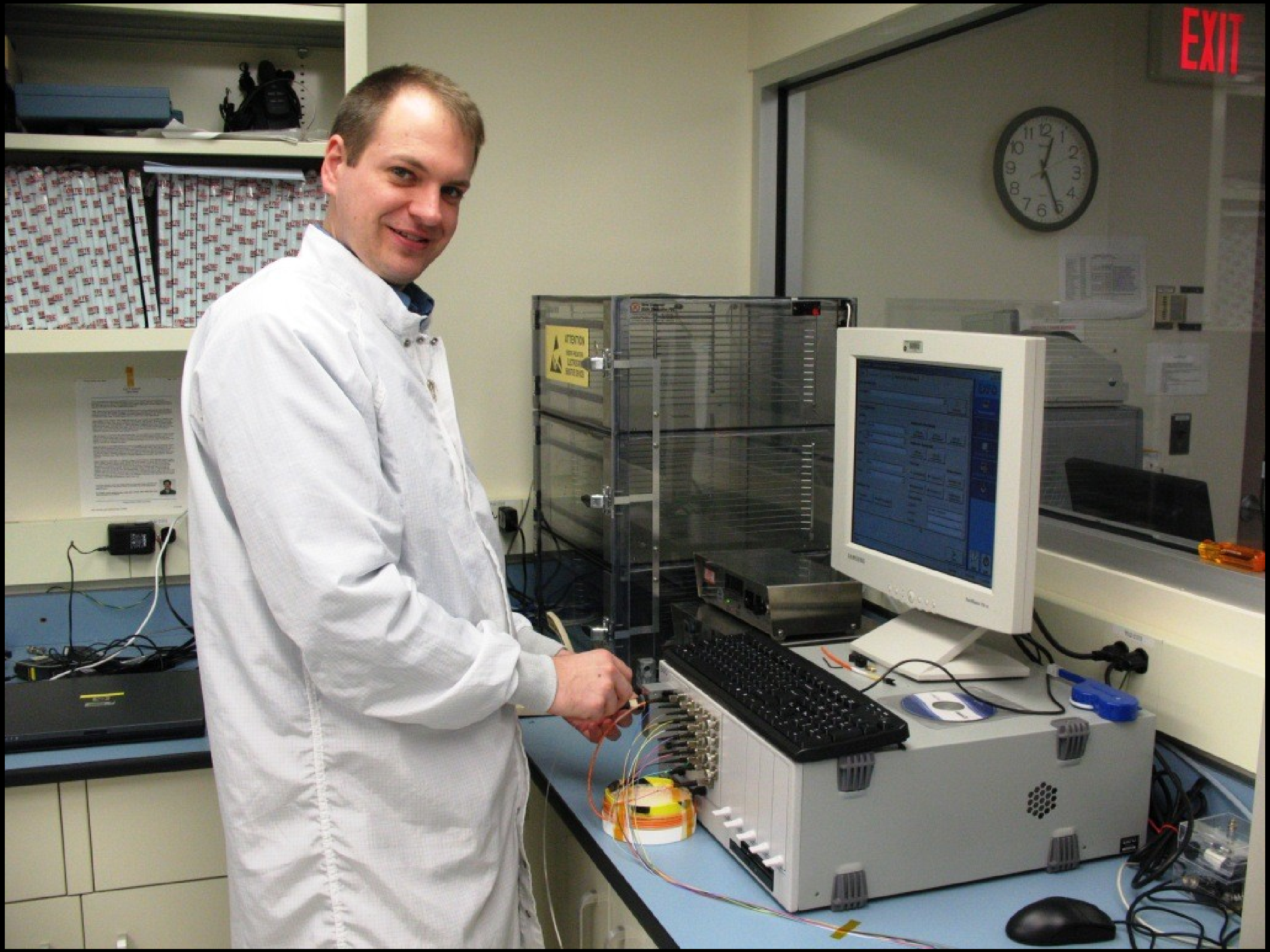
Document Name	CM Document Number
Optical Cable Inspection	562-PHOT-QAD-MSL-FON1482-INSP
Cable Thermal Pre-Cond	562-PHOT-QAD-MSL-THERM-PC
Polymers Degas	562-PHOT-WOA-MSL-BOOTS (Hytrel degas @ Materials)
Mission Survival Radiation Total Dose Testing	562-PHOT-QAD-MSL-RAD (12-day worst-case cobalt60 radiation testing)
Mission Survival Vibration Qualification	562-PHOT-QAD-MSL-VIBE (7.9grms to 14.4grms step-up vibration on selected samples)
Mission Survival Thermal Cycling Testing	562-PHOT-QAD-MSL-THERM-CYCLE (100+ cycles including planetary bake-out)
FC Cable Manufacturing (non-flight)	562-PHOT-QAD-MSL-MAN-92 (Patch Cables)
AVIM Cable Manufacturing (non-flight)	562-PHOT-QAD-MSL-MAN-92-332 (Prototype Development)
AVIM Cable Manufacturing (flight-like)	562-PHOT-QAD-MSL-MAN-332-EM (Eng Models)
AVIM Cable Manufacturing (FLIGHT)	562-PHOT-QAD-MSL-MAN-332-FM (FLIGHT and FLIGHT Spares)
Insertion Loss Testing (All-Cables)	562-PHOT-QAD-MSL-INS-92-332 (Insertion Loss testing Pre and Post all tests)
Non-flight Cable Workmanship Testing	562-PHOT-QAD-MSL-WKM-92-NONFL (Non-flight workmanship)
FLIGHT Workmanship Testing	562-PHOT-QAD-MSL-WKM-332-FLIGHT (FLIGHT workmanship)
MSL CABLE TRAVELER	GSFC-PHOTONICS CABLE TRAVELER REV 080101
Engineering Documents Review	GSFC-PHOTONICS ENGINEERING DOCUMENT REVIEW (Lead Manufacturing, Project Lead)
Pre-Shipment Inspection Checklist	GSFC-PHOTONICS PRE-SHIPMENT PROCEDURE CHECKLIST
Cable Packing Procedure Checklist	GSFC-PHOTONICS PACKING PROCEDURE CHECKLIST

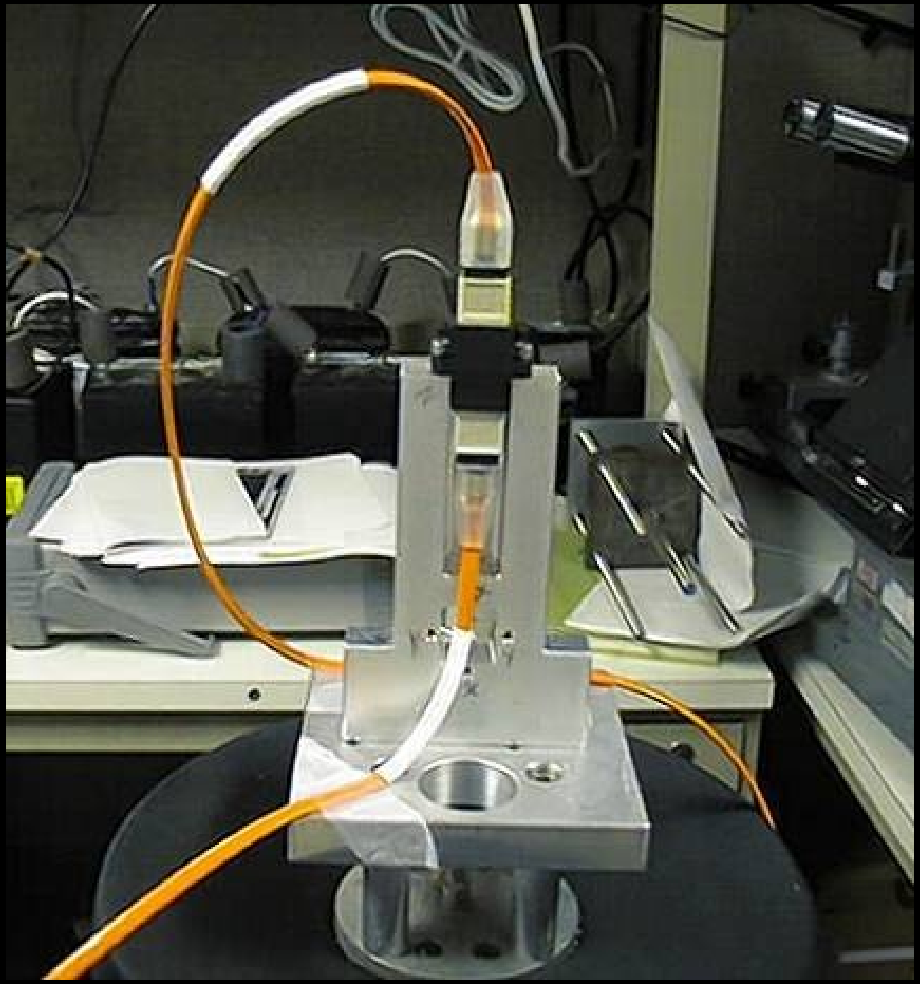
Express Logistics Carrier, Connection to ISS AVIM connectors – Flexlite Cable

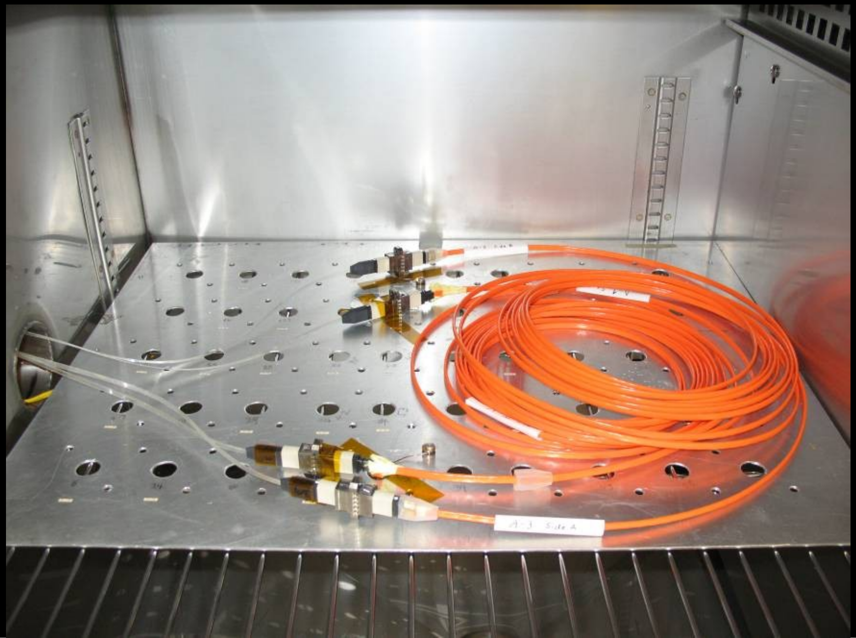


Fiber Optic Flight Assemblies for Space Photonics Transceiver Inspection, Preconditioning, Manufacturing, Testing and Workmanship Procedure, (As Run Format)
ELC PROC 000400

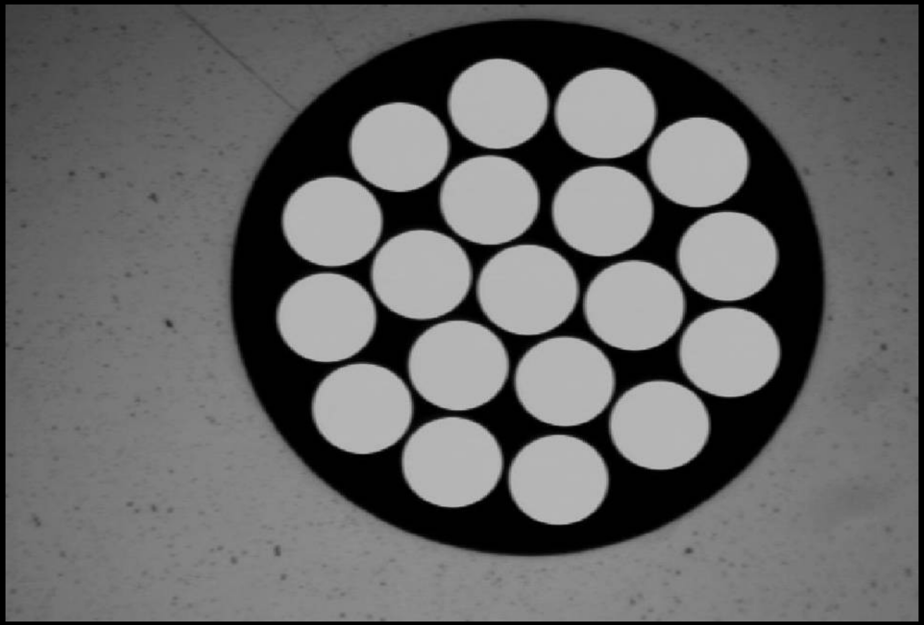
The MTP Connector for Communications Support to NASA & DOE, Sandia Qualification Testing of the MTP, 1998 - 2008







2008 New Capability
19 Fiber Arrays with Linear to Bundle Mapping



High Power Fiber Terminations

All designs use space-qualified materials

Some Lessons Learned

- Know your failure modes or higher an expert to do it for you.
  - ✓ Materials analysis now or later, you decide.
  - ✓ Vendors get information from outgassing database – its not stand alone

- Cracked fiber doesn't mean catastrophic failure unless you are photon counting.

- Need experts to review documentation.

- Need good quality documentation;
  - ✓ Pre-manufacturing preconditioning of materials.
  - ✓ Incoming inspection of all vendor supplied items.
  - ✓ Manufacturing procedures.
  - ✓ Post manufacturing visual inspections for compliance.
  - ✓ Post manufacturing workmanship.

Conclusion

Redundancy is used to reduce risk in communication systems.

Optical fiber systems have been used in space flight for thirty years successfully.

Knowledge of failure modes and materials is crucial to making feasibility decisions as well as design, manufacturing procedures and test plans.

GSFC can supply expertise to reduce risk at any given step.

Thank you
for the invitation!

For more information please visit the website:
http://photonics.gsfc.nasa.gov

What Else You Got?

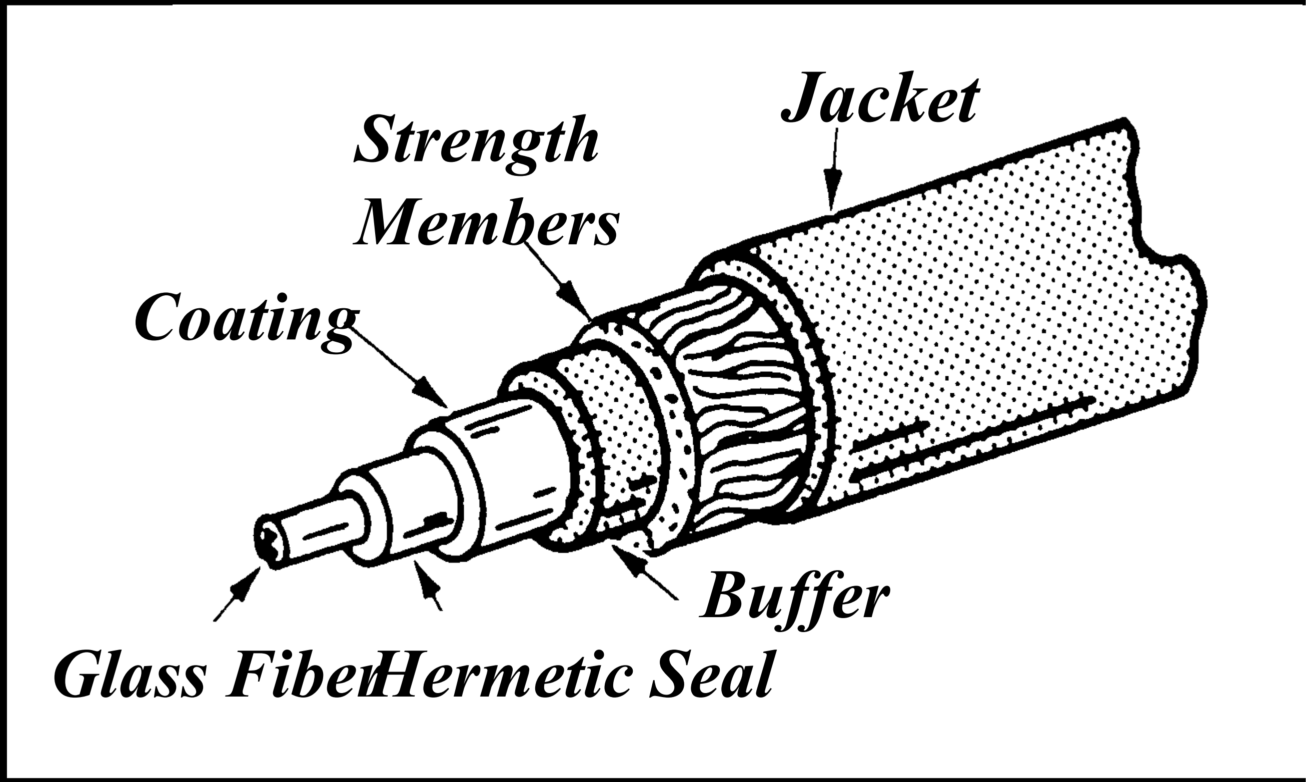
Slides for general information on
space flight optical fiber systems continued…..

International Space Station 2000, Lead by GSFC

Failure Analysis: Optical Fiber Cable 1999-2000

Failure Analysis: Optical Fiber Termini 2005-2006,
Lead by GSFC

Bad combination of physics



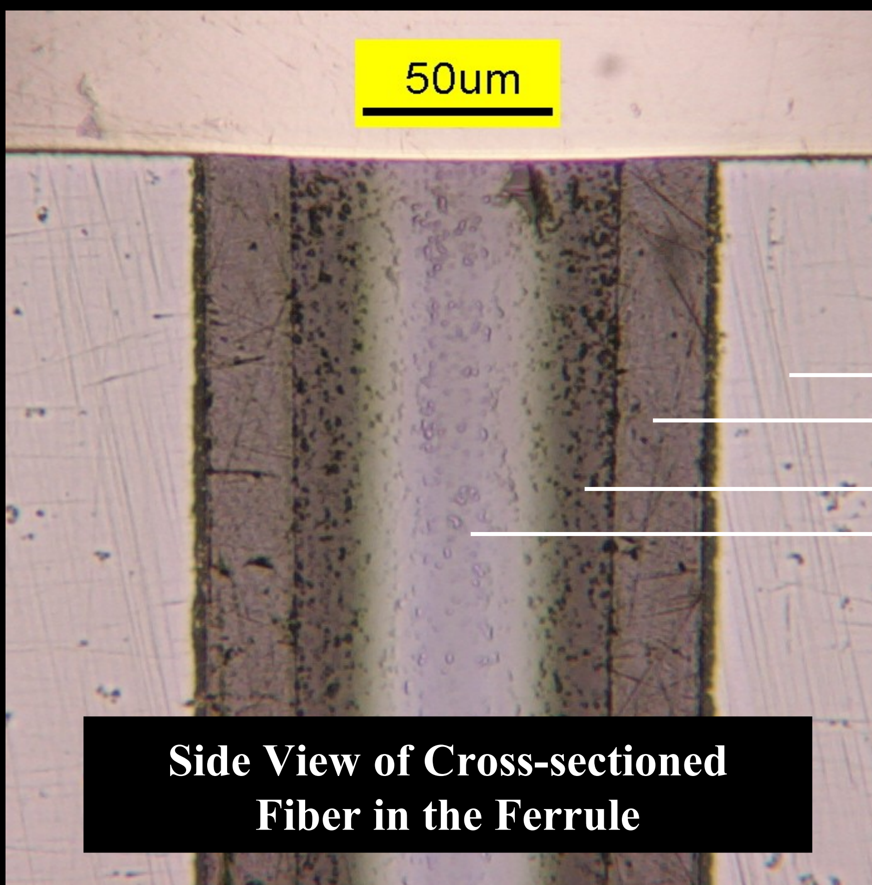
Fiber Optic Cable "Rocket Engine" Defects

Hermetic coating holes,
Polyimide coating holds water
Fluorine generated during extrusion of buffer
Hollow tube construction
water and fluorine interaction results in HF acid
HF etches pits into fiber getting through holes in coating
Etch pits deep into the core caused losses and cracks

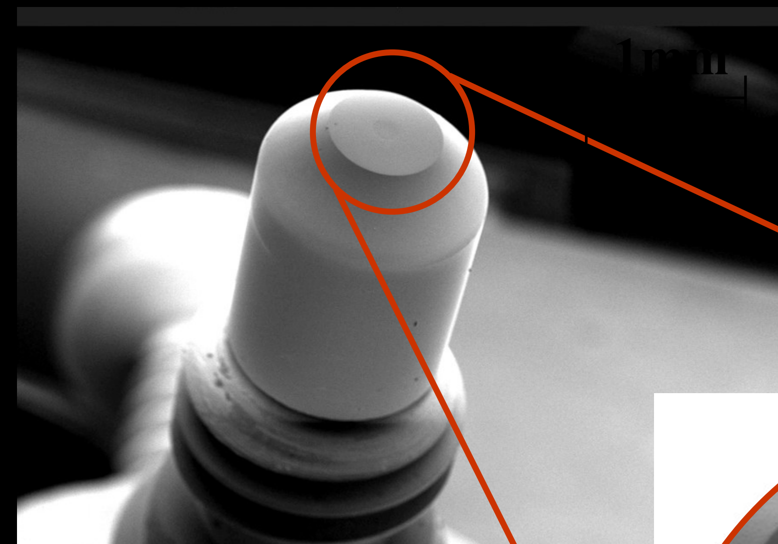
Conclusion; We don't recommend hermetic coatings.

ISS Termini Failure Analysis

The below cross section of the terminus shows a concave end-face. This is per specification. If the end-face were convex, the glass would likely experience an impact when connected, causing a fracture.



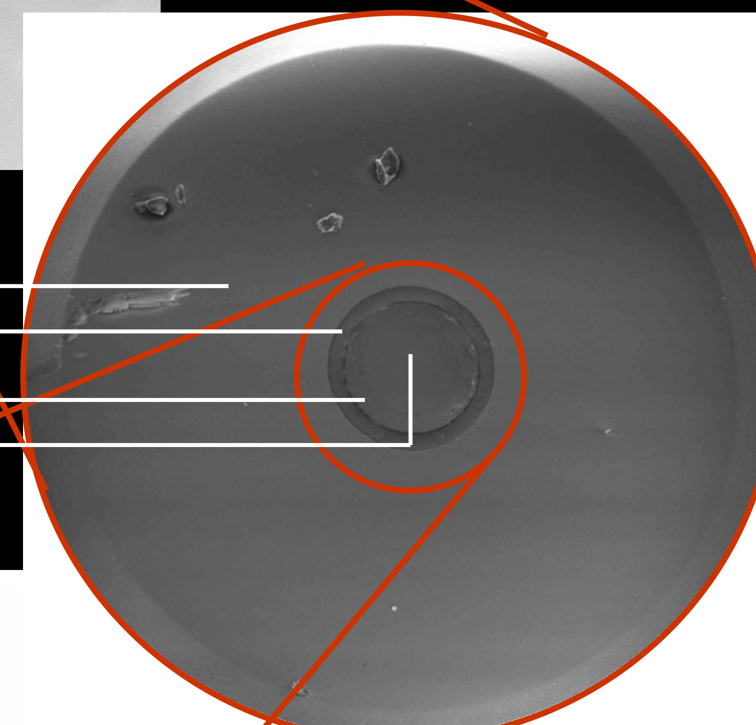
Side View of Cross-sectioned Fiber in the Ferrule



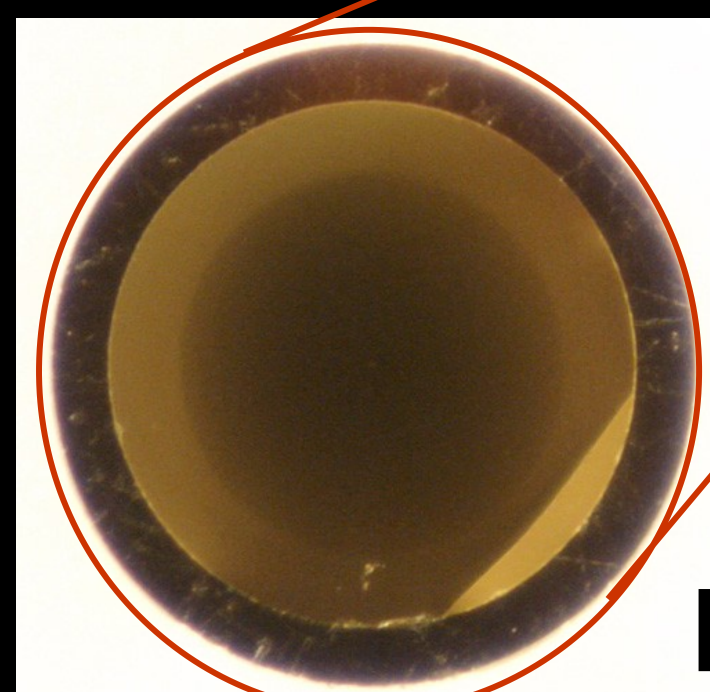
The fiber must be free of cracks in order to prevent a degraded or blocked optical signal. If a glass fiber has a crack after the polishing process, the crack will grow over time.

<u>The termination is made up of:</u>

A zirconia ferrule
Polyimide coating
Pure silica cladding
Germanium doped core



Ferrule & Fiber End View



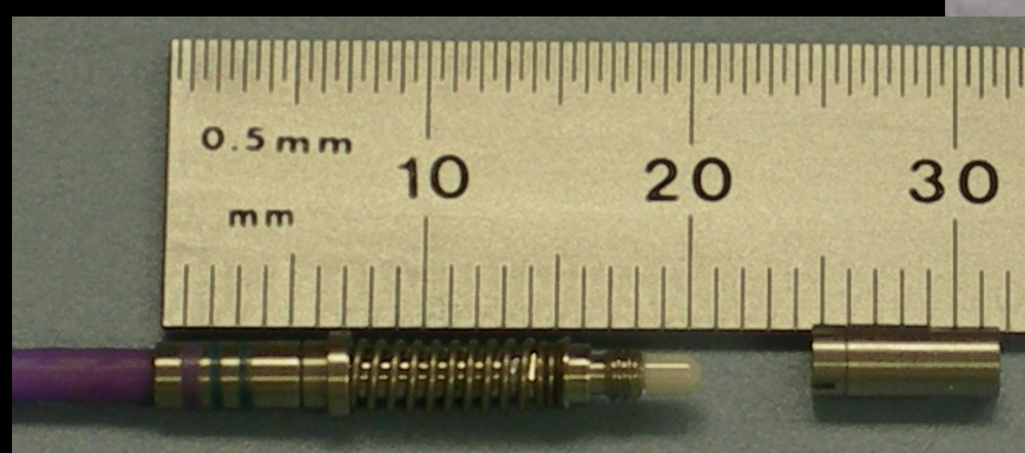
The end-face of this optical fiber is 140µm. If dirt is present, the optical signal would be degraded or blocked.

Core, Cladding, & Coating End View

International Space Station Study on Termini 2006
Performed at GSFC, Code 562

1) Lack of space flight termination expertise – Manufacturing.
2) Lack of sufficient quality final inspection - Manufacturing
3) Lack of incoming inspection and handling – Integrator.

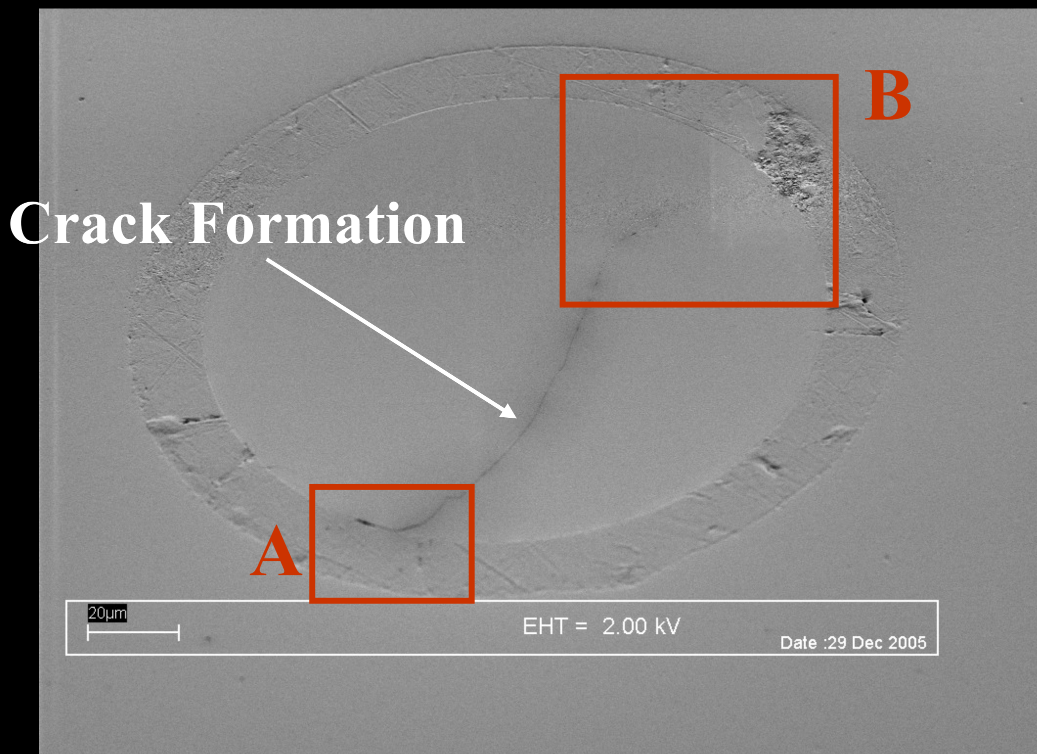
32 termini are installed into one "MIL-C-38999" type connector.



Termini end faces were found to be cracked after failing insertion loss testing during integration.

ISS FA Scanning Electron Microscopy

Fiber Most Likely to Fail Because of Crack

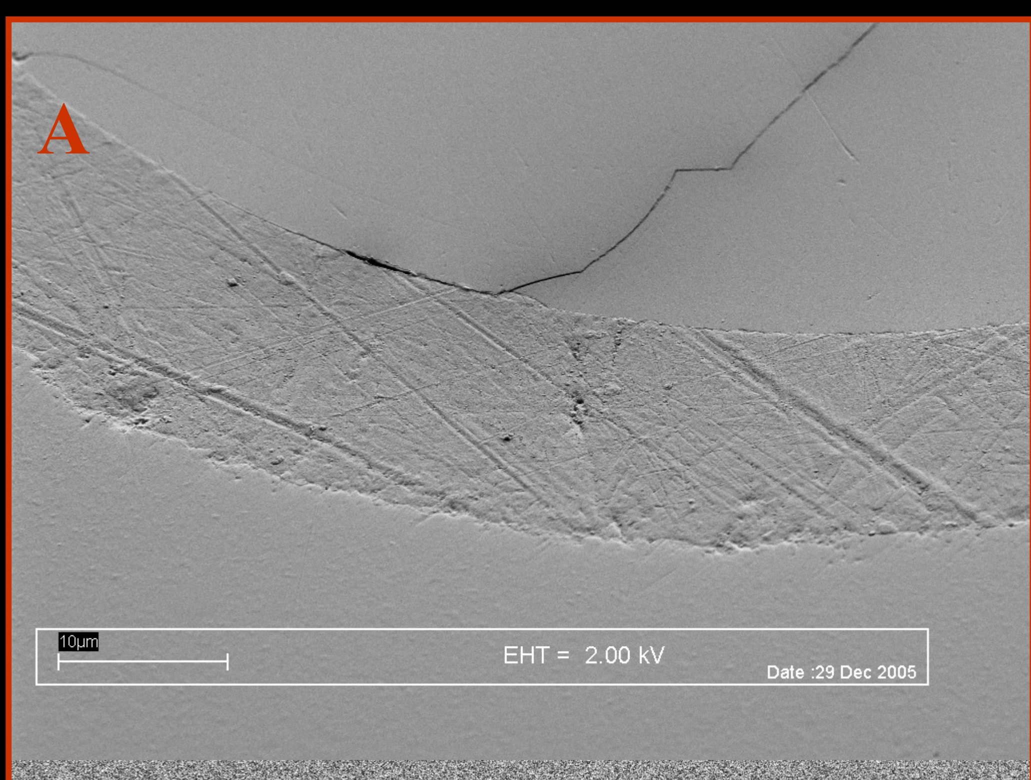


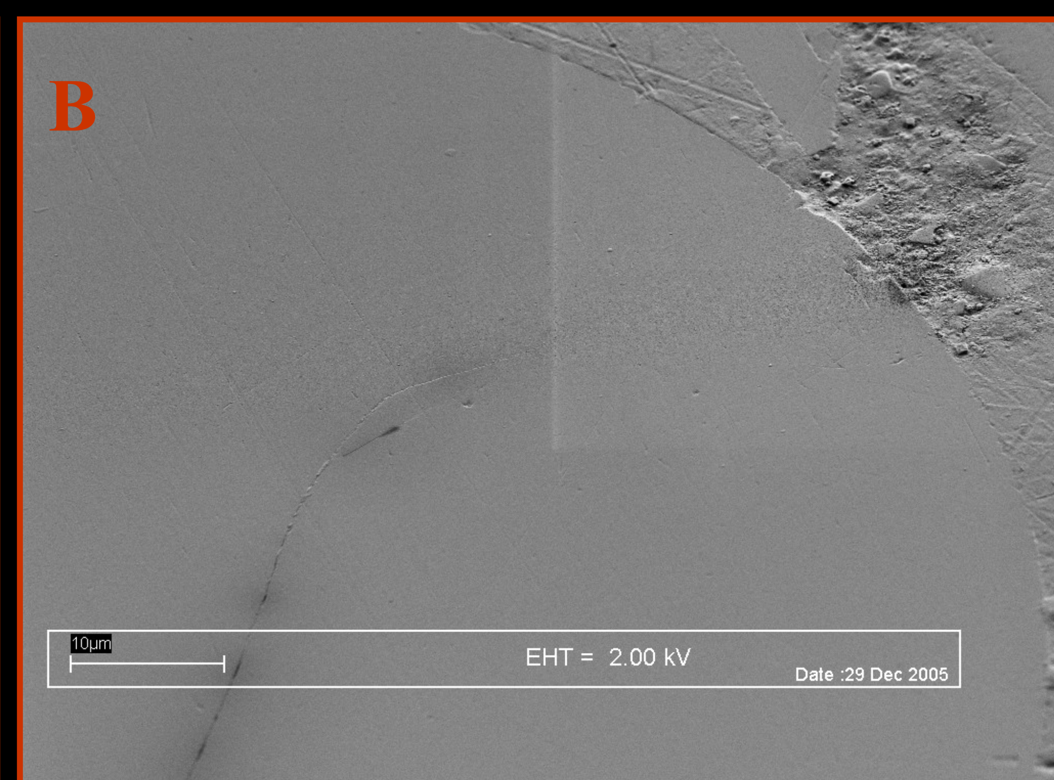
Scanning Electron Microscopy (SEM):

•SEM gives a clear image of the crack, and could be observed at over 50000X magnification.

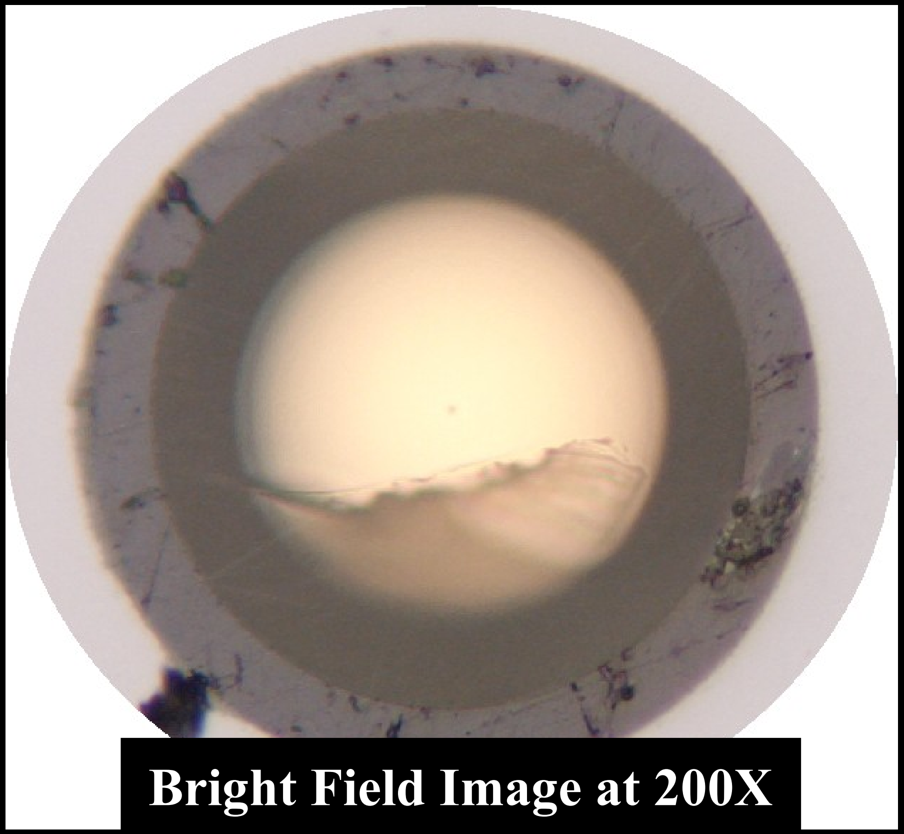
•At 500X, the ends of the crack can be observed and analyzed.

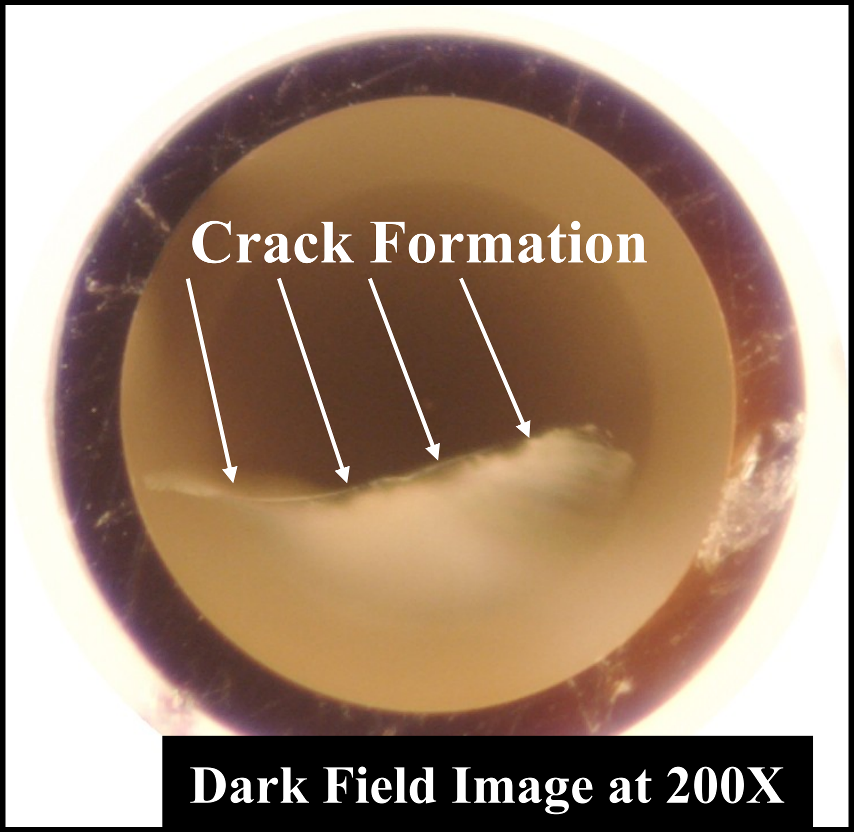
•A concave or convex profile of the end-face cannot be determined using the SEM, so the terminus must be evaluated using confocal microscopy.





ISS FA Optical Microscopy





Optical Microscopy:

•Bright field (Top) & dark field (Bottom) illumination (taken at 200X) can be used to enhance certain features of the terminus.
•At 200X, a crack formation can be seen, and the "smudge" appears to be sub-surface cracking.
•More information is required to characterize the crack.
•Optical microscopy is not enough to identify an origin of the crack, so SEM will need to be performed.

Materials Issues
Shuttle Return to Flight: Construction Analysis

Optical Fiber Pigtailed Collimator Assemblies

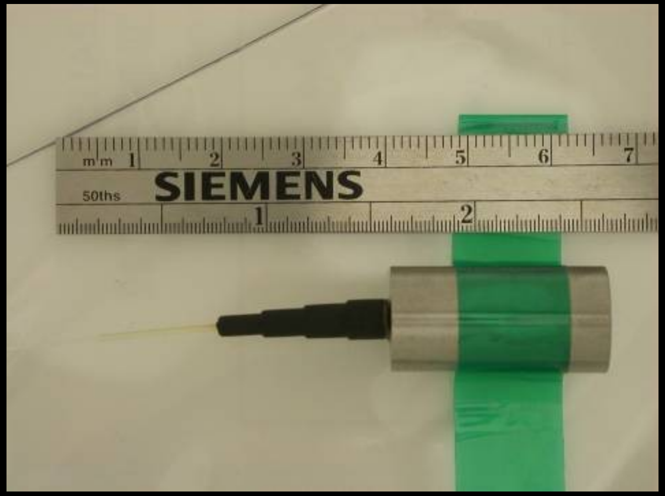
Lightpath: pigtailed fiber to collimator lens and shell

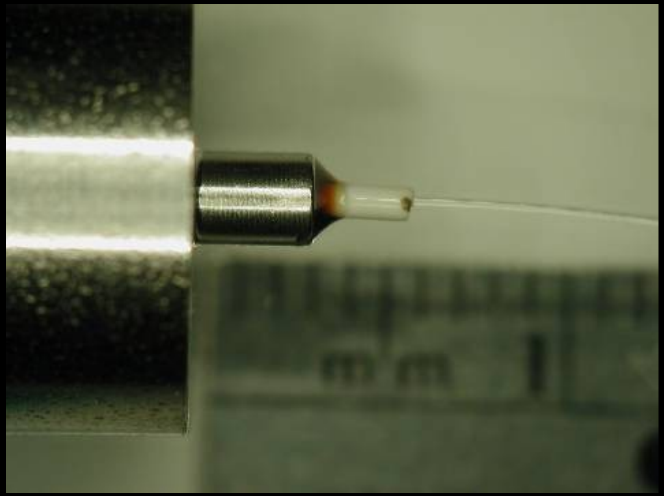
GSFC: upjacket (cable), strain relief and termination, AVIMS, PC, SM

Materials & Construction Analysis

- Non compliant UV curable adhesive for mounting lenses to case
  - Solution 1: replace with epoxy, caused cracking during thermal cycling
  - Solution 2: replace with Arathane, low glass transition temp. adhesive

  Lesson: coordinate with adhesives expert, care with adhesive changes.
- Hytrel, non compliant as an off the shelf product (outgassing, thermal shrinkage)
  - Thermal vacuum preconditioning (145°C, <1 Torr, 24 hours)
  - ASTM-E595 outgas test to verify post preconditioning.
  - Thermal cycling preconditioning (30 cycles, -20 to +85°C, 60 min at +85°C)



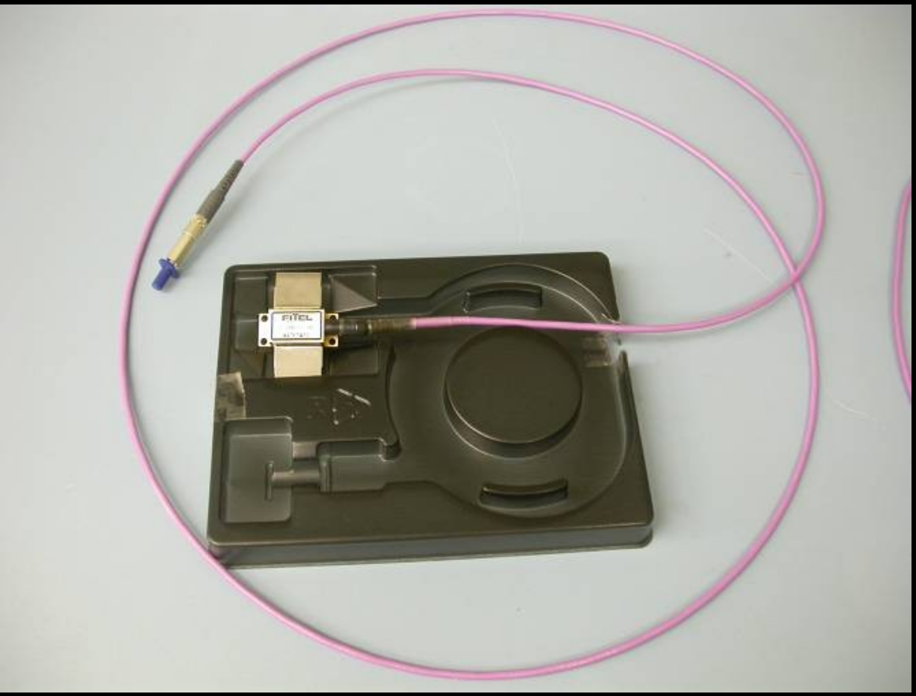


Materials Issues: Shuttle Return to Flight

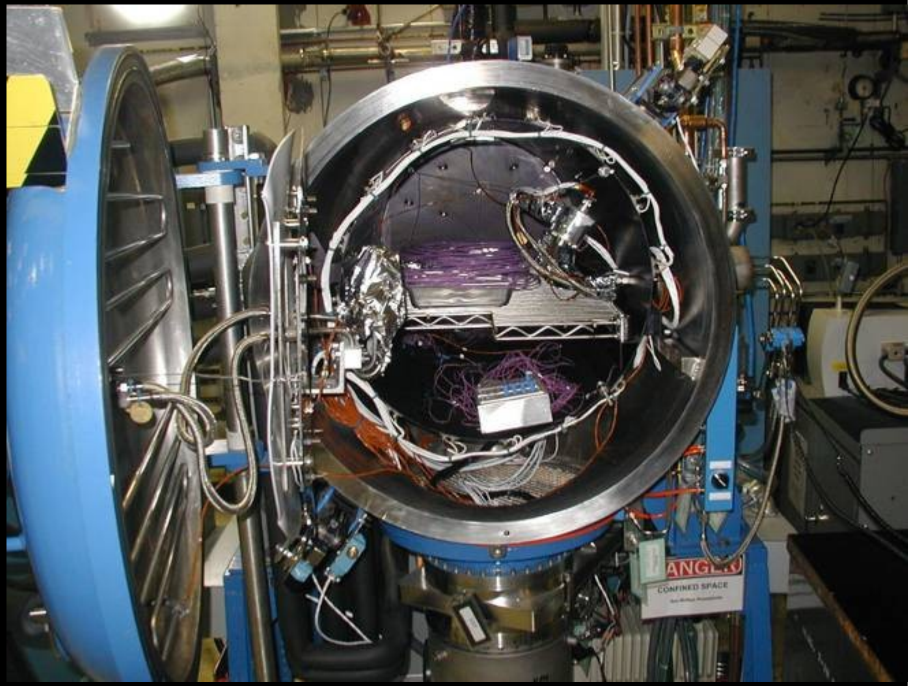
Laser Diode Assemblies

Fitel: laser diode pigtails
GSFC: Upjacket (cable), strain relief, termination, AVIMS APC SM
Fitel uses silicone boot, non-compliant!
Too late in fabrication process, schedule considerations to preprocess.

Cable: Thermal preconditioning, 30 cycles
Hytrel boots: Vacuum preconditioning, 24 hours
Kynar heat shrink tubing, epoxy: approved for space use.



Post manufacturing decontamination of entire assembly required
Laser diode rated for 85°C processing performed at 70°C

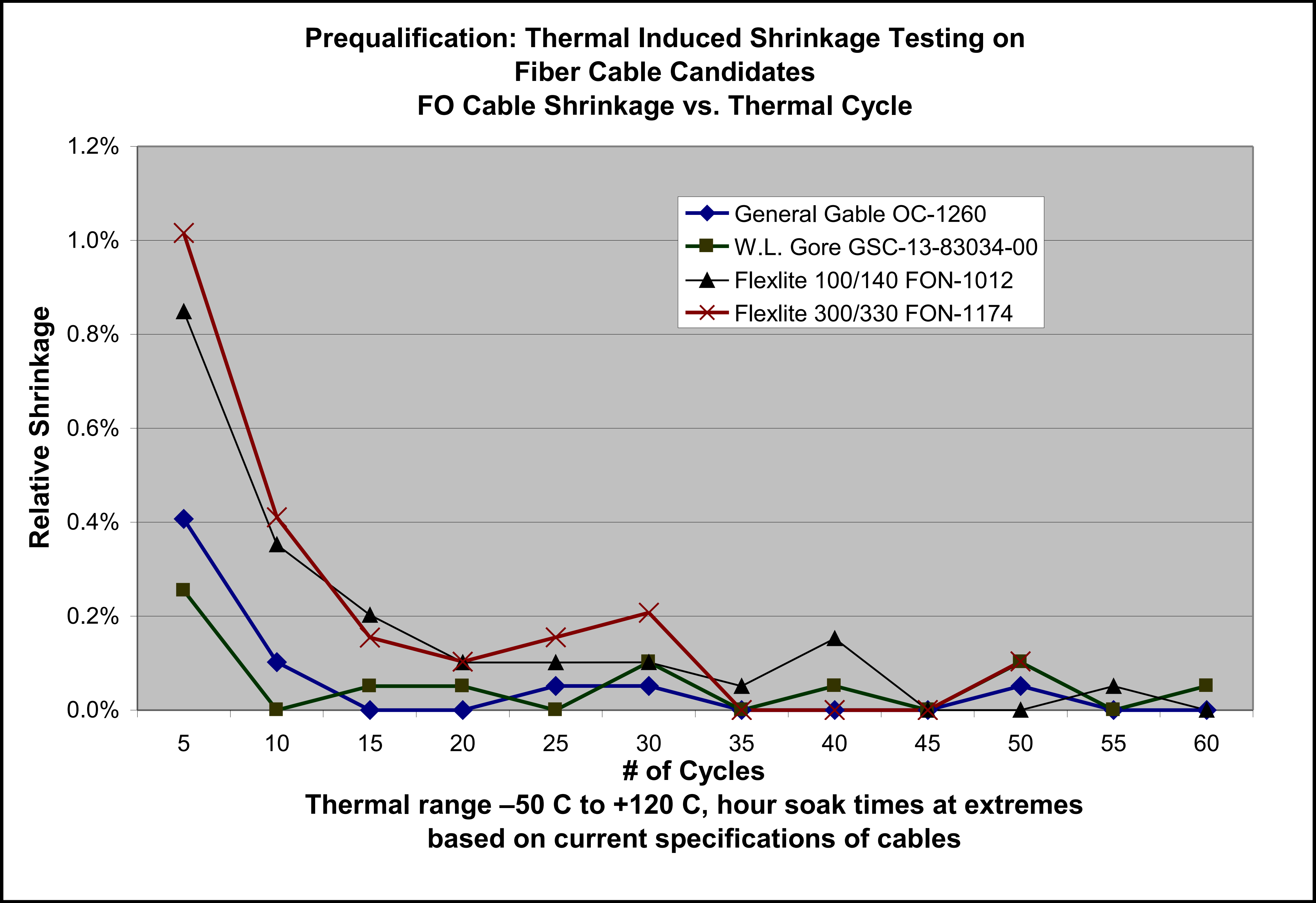


Thermal Effects

Thermal stability is dependent on;

- Cable construction
  - Outer diameter (smaller=more stable).
  - Inner buffer material (expanded PTFE excellent).
  - Extrusion methods (polymer internal stresses).
- Preconditioning
  - 60 cycles usually keep shrinkage less than 0.1%
  - Survival limits (hot case) is used for cycling.
  - Cut to approximate length prior.
- Termination
  - Ferrule – Jacket isolation necessary.
  - Polishing methods (especially at high power).

ISS Cable Candidates; Thermal Screening for Shrinkage



Because fluoropolymers have thermal shrinkage issues.

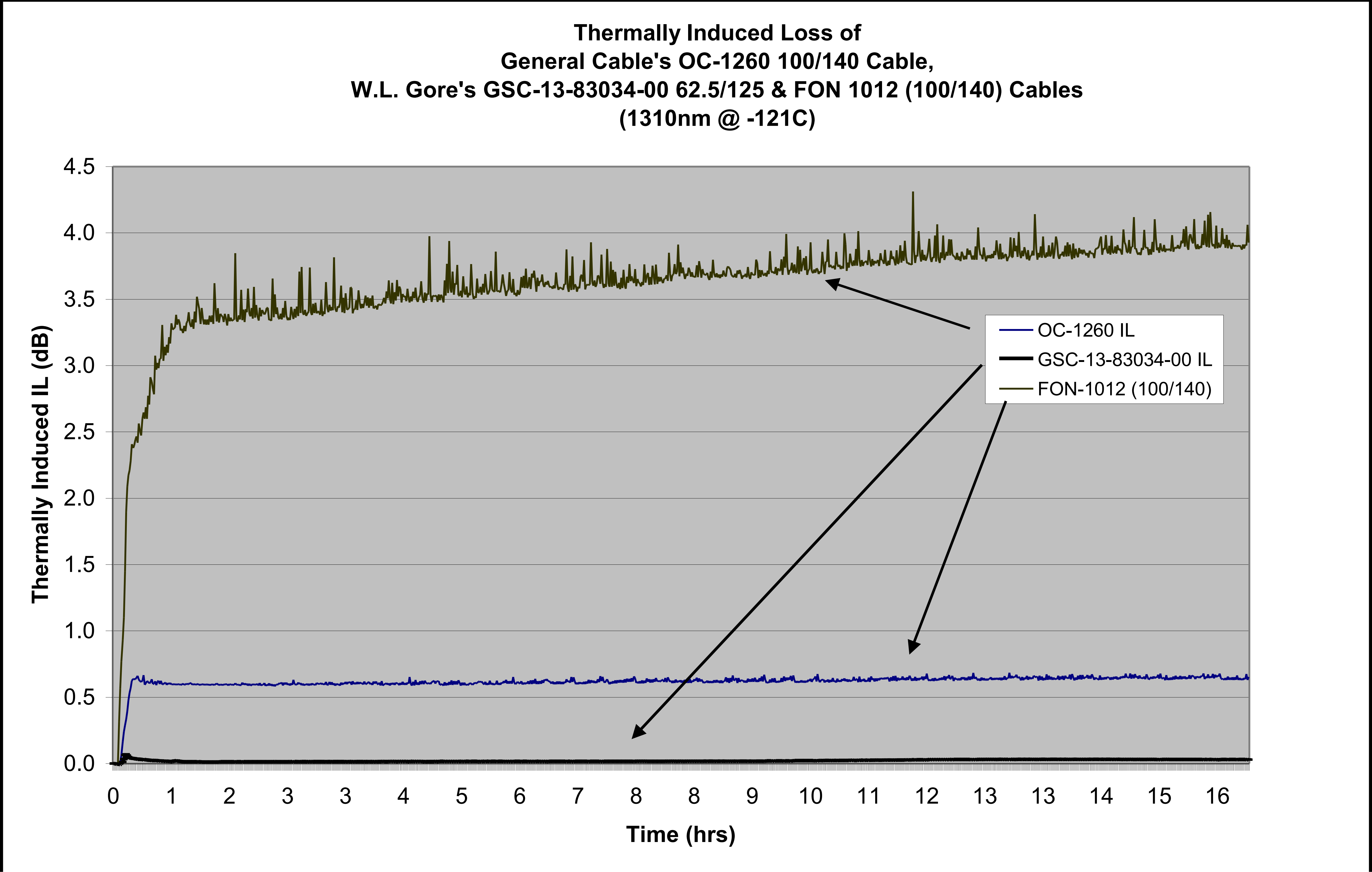
ISS Cable Candidates; Thermal Pre Qual, -121°C

Manufacturer	Part Number	Fiber Type	Thermal Range
W.L Gore	FON1012, FLEX-LITE™	OFS BF05202 100/140/172	-55 to +150°C
General Cable	OC-1260	Nufern (FUD-2940) 100/140/172	-65 to + 200°C
W.L Gore	GSC-13-83034-00 1.8 mm	Nufern (FUD-3142) 62.5/125/245	-55 to +125°C

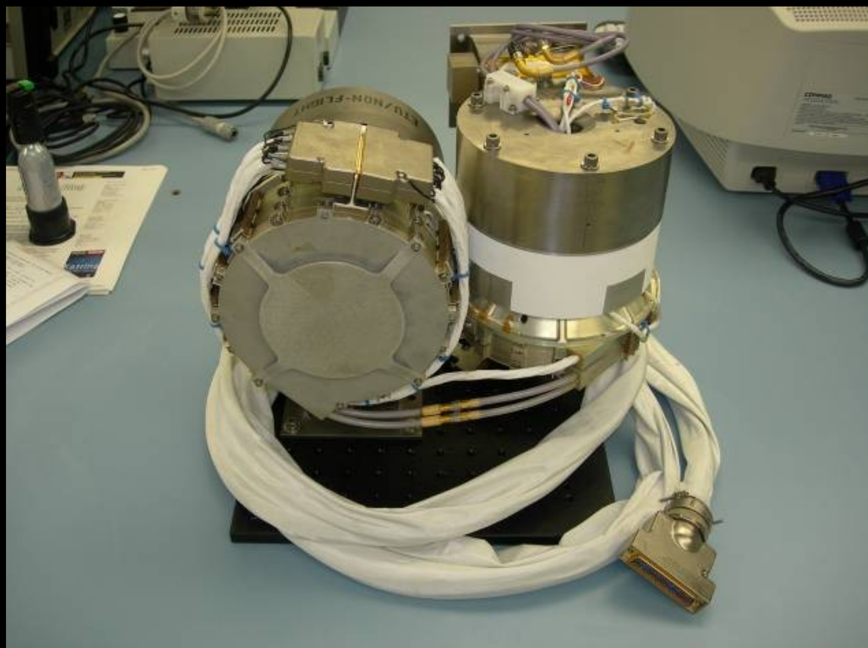
The above cable candidates were tested for 16 hours at -121°C

ISS Cable Candidates; Thermal Pre Qual, -121°C

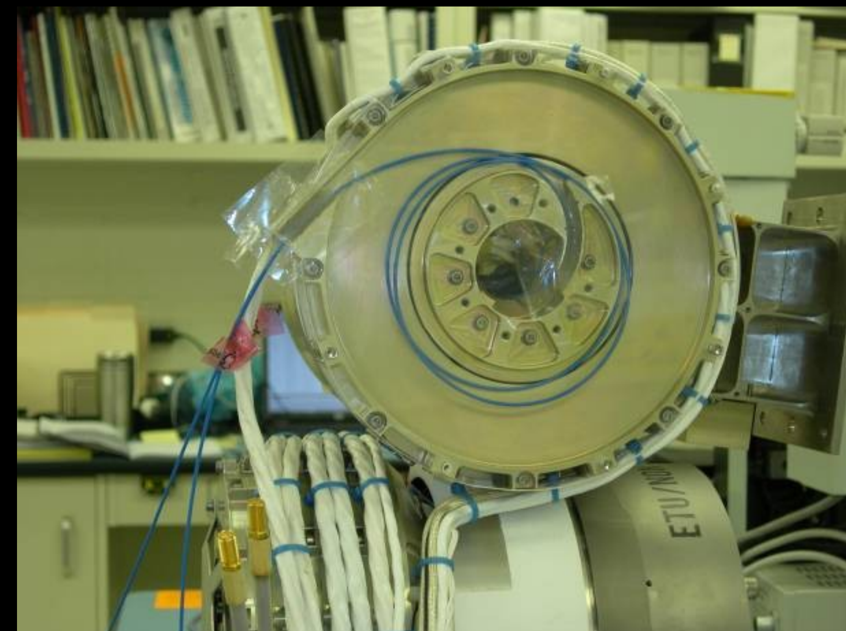
9 meters



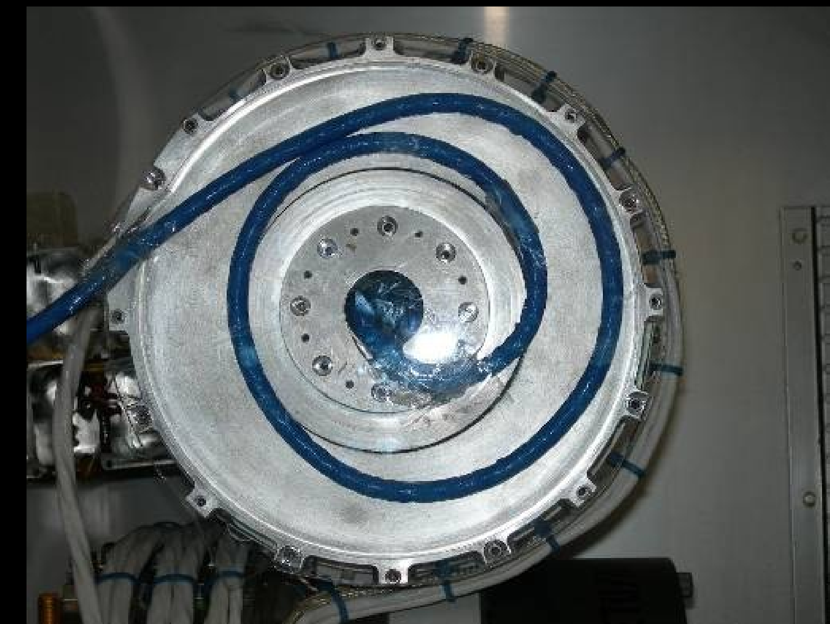
LRO Laser Ranging Cold Gimbal Motion Life Testing



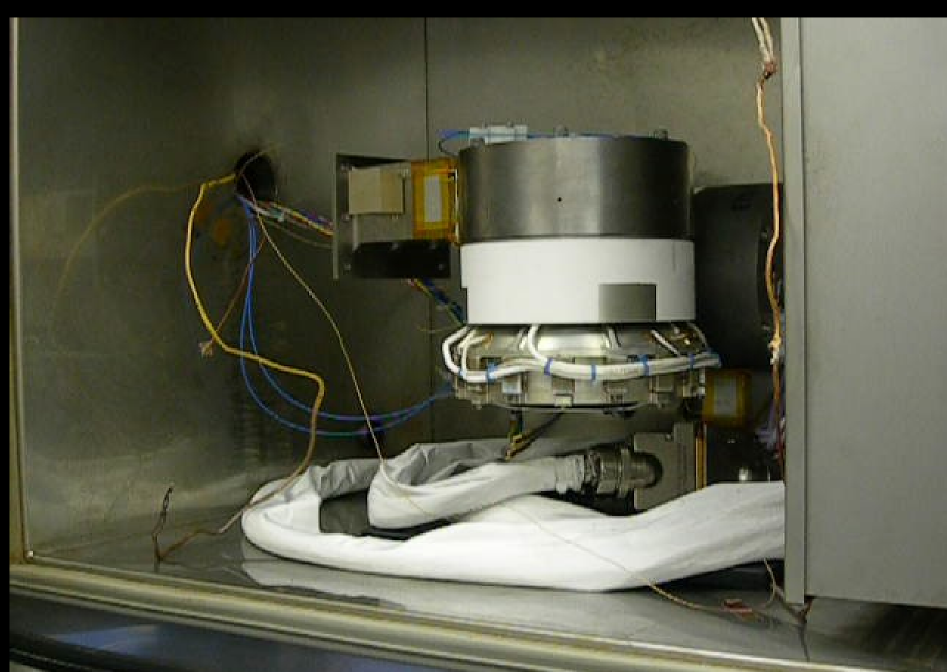
Gimbals



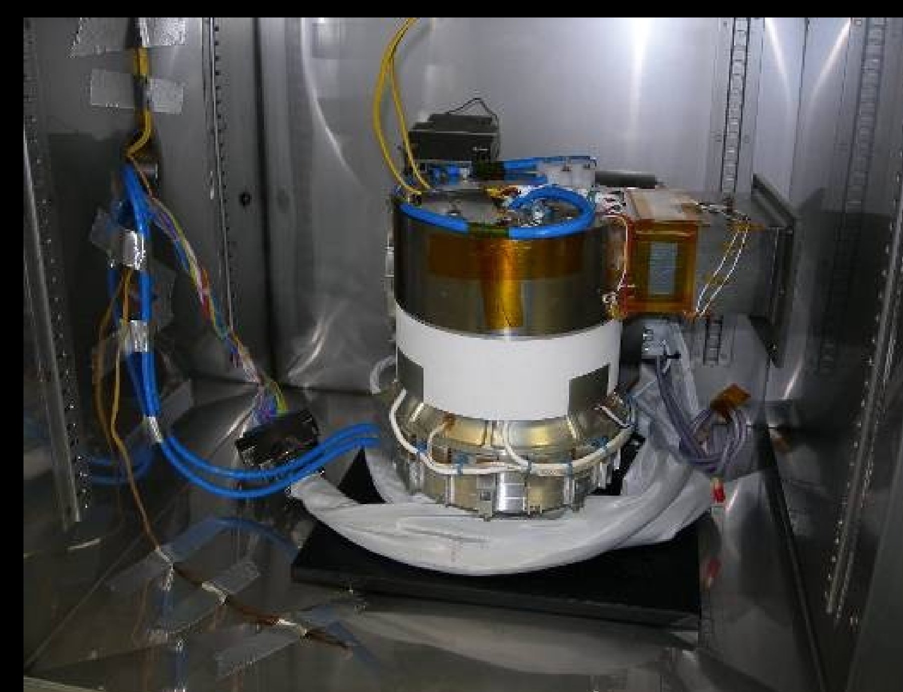
Window inside gimbal;
Flexlite cable inside



Window inside gimbal;
Bundle cable inside.



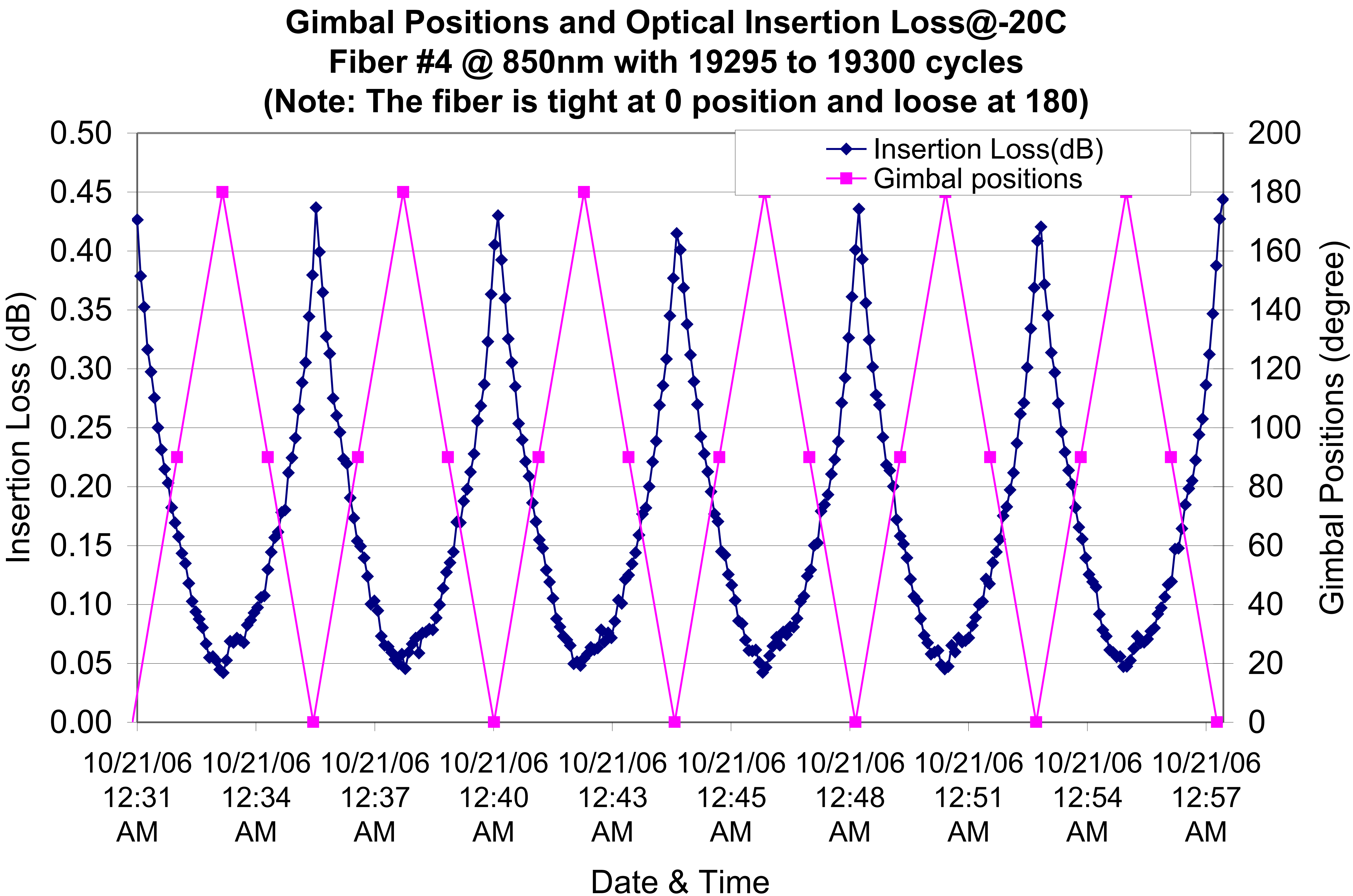
Gimbals w/ single flexlite in thermal chamber



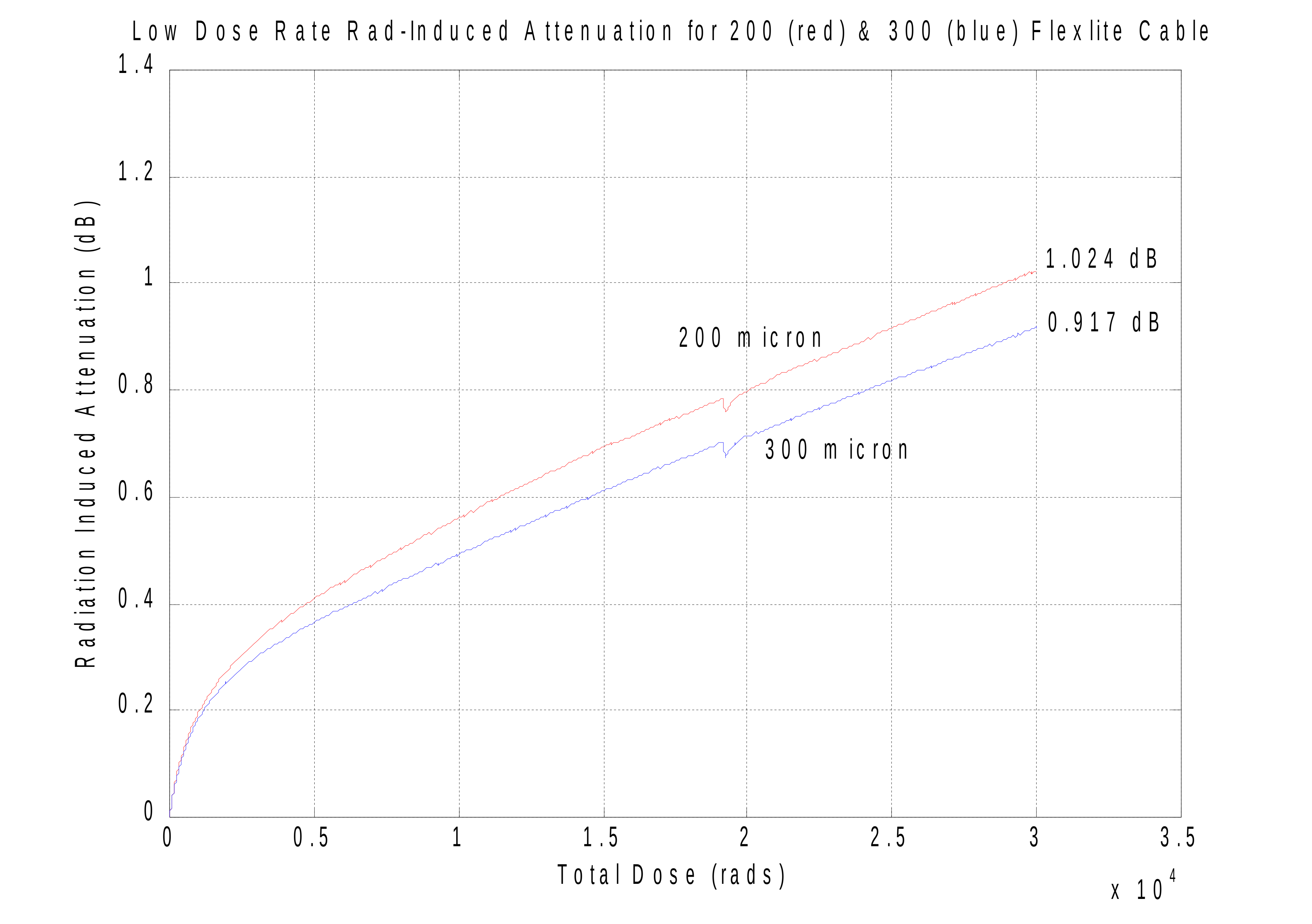
Gimbals w/ bundle in thermal chamber

LRO Laser Ranging Bundle Cold Gimbal Motion Testing Results

End of Test, relative IL ~ 0.50 dB, @ 850 nm, -20°C, 400/440 FV flexlite in Bundle



Radiation Effects Mercury Laser Altimeter



Flexlite Radiation Test, 11.2 rads/min at –24.1°C

Radiation Conclusion: < .07 dB, using 11.2 rads/min, -24.1°C, 26.1 in, “dark”

Results for 10 m, at 30 Krads, -20°C, 850 nm, 23 rads/min ~ 1 dB or 0.10 dB/m

MLA Radiation Data, Does Core Size Matter?

There is only about 0.0074 dB/m difference between the Polymicro 200/220um fiber and the Polymicro 300/330um fiber. Size makes very little difference since 200 more susceptible as well.

Table 5: Summary of Radiation Induced Attenuation on MLA Assemblies

Part Number	Fiber Type (microns)	Dose Rate	Atten @ 30 krads	Ave.Temp during Test	Expected Atten 26.1 inches @ 30 krads
FON1173	200	11.2 rads/min	1.024 dB	-24.1 ℃	.068 dB
FON1174	300	11.2 rads/min	0.917 dB	-24.1 ℃	.061 dB
FON1173	200	22.7 rads/min	0.892 dB	-18.3 ℃	.059 dB
FON1174	300	22.7 rads/min	0.818 dB	-18.3 ℃	.054 dB

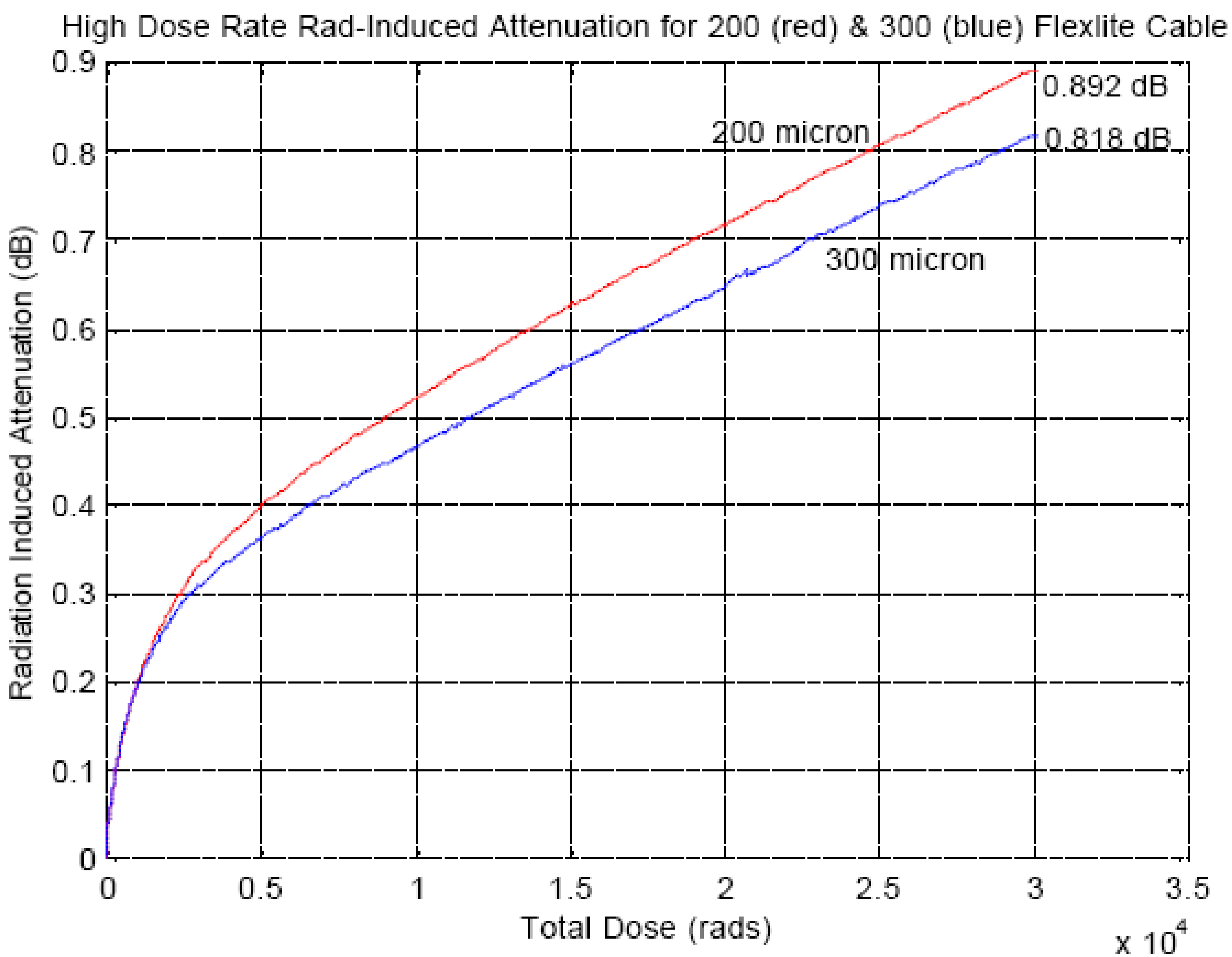
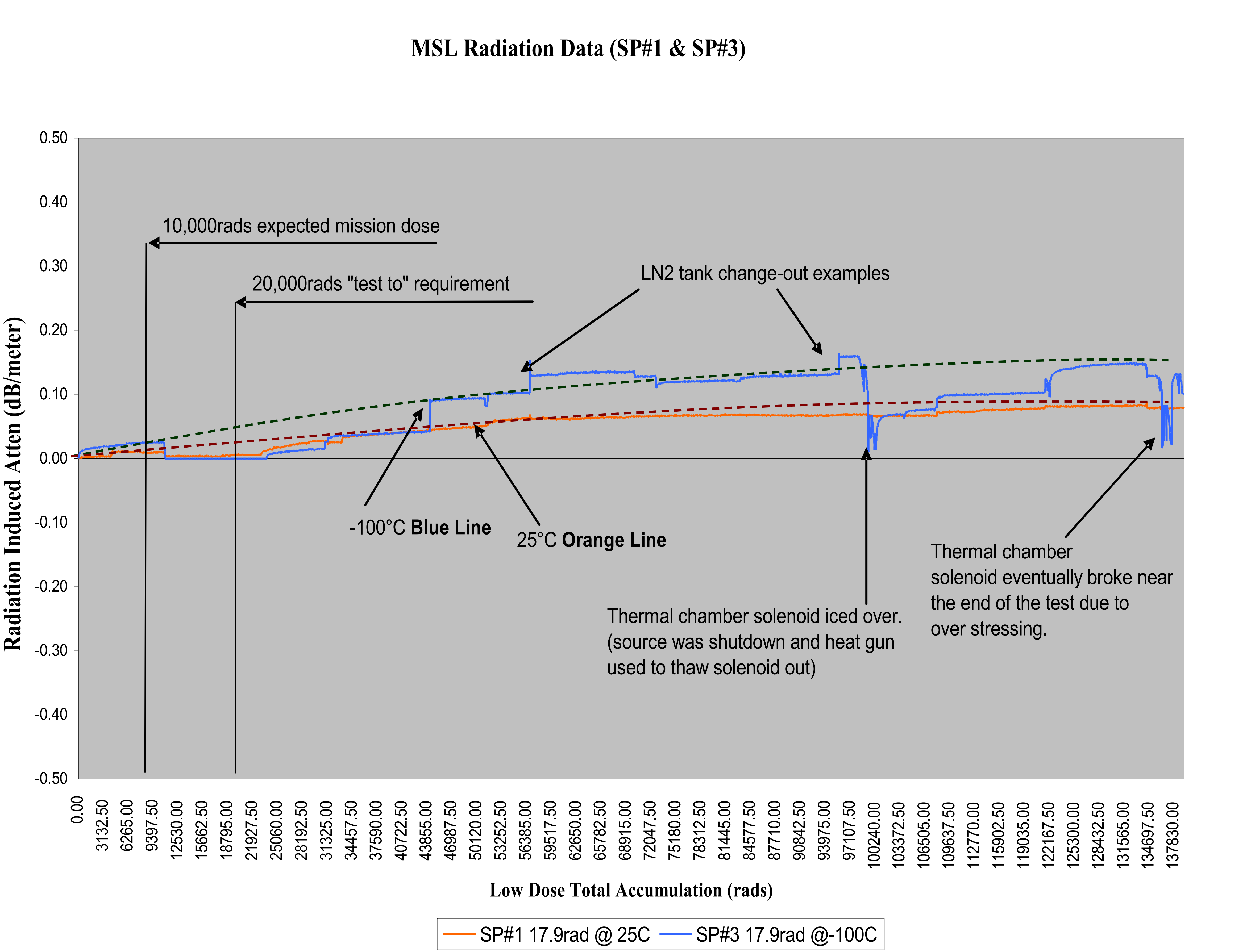


Figure 10: High Dose Rate Test Results to 30 krads of the 200 and 300 micron Optical Fiber FLEX-LITE™ Cable (10 meters).

MSL Radiation Requirements using the LRO Radiation Model @ 532 nm, for the Polymicro FV400/440 (.22 NA)

Duration	Dose Rate Rads/min	Total Dose	Temperature	Attenuation
36 months	0.0064	10 Krad	-80 C	0.0015 dB/m
36 months	0.0126	20 Krad	-80 C	0.0030 dB/m
8 months	0.0289	10 Krad	-80 C	0.0025 dB/m
8 months	0.0578	20 Krad	-80 C	0.0049 dB/m

MSL Nufern Radiation Test Results



MSL 300/330 Nufern Summary @ 330 – 450 nm

Total Dose	Dose Rate	Temp	Attenuation
10 Krad	17.9 rads/min	25°C	< 0.05dB/m
20 Krads	17.9 rads/min	25°C	< 0.05dB/m
10 Krad	17.9 rads/min	-100°C	< 0.05dB/m
20 Krads	17.9 rads/min	-100°C	~0.05dB/m

In general decreasing the dose rate 3 orders of magnitude decreases the attenuation by 1 order of magnitude. Comparing FV series to the Nufern 300/330
Nufern 300/330 ~ 0.005 dB/m for 20 Krads, -100°C, 300 – 450 nm
PolyM FV 300/330 ~ 0.003 dB/m at 20 Krads, -80°C, 532 nm

Aluminum content increases radiation induced effects [1]

Yb (mol %)	Al_2O_3 (mol %)	P_2O_5 (mol %)	TID Krad	Rad Induced Atten.
0.13*	1.0	1.2	14	1 dB/m
0.18	4.2	0.9	14	12 dB/m

*** Fiber also contains 5.0 mol% Germanium. Data at 830 nm, 180 rads/min.**

Rare Earth dopant (Er) does not dominate over radiation performance [2]

Part	Er Content	Al (%mol wt)	Ge (%mol wt)	Sensitivity 980 nm, dB/m Krad	Sensitivity 1300 nm, dB/m Krad
HE980	$4.5\ 10^{24}\ /m^3$	12	20	.013	.0041
HG980	$1.6\ 10^{25}\ /m^3$	10	23	.012	.0038

84 rads/min upto 50 Krad, 3 m under ambient

[1] H. Henschel et al., IEEE Transactions on Nuclear Science, Vol. 45, Issue 3, June 1998, pp. 1552-1557.
[2] T. Rose et al., Journal of Lightwave Technology, Vol. 19, Issue 12, Dec. 2001, pp. 1918-1923.

Low Dose Rate, .038 rads/min extrapolation for HE980

Wavelength	Total Dose	Radiation Induced Attenuation
980 nm	100 Krad	0.91 dB/m
1300 nm	100 Krad	0.26 dB/m
1550 nm	100 Krad	0.14 dB/m

Also shows wavelength dependence, consistent with other COTS fiber.

Yb and Er doped fibers are equivalent in terms of sensitivity.

Lanthanum doped fibers are extremely sensitive at ~10's dB/m.

Yb and Er doped fibers exhibit saturation behavior.

Proton and gamma exposures show similar results.

To compare sensitivity to typical 100/140 at 100 Krads

Temp	λ nm	Dose rate	Sensitivity	Reference
25°C	1310	.01 rads/min	$1.7\ 10^{-4}$ dB/m	M. Ott, SPIE Vol. 3440.
50°C	850	.032 rads/min	$2.0\ 10^{-4}$ dB/m	M. Ott, IEEE NSREC Data Workshop 2002.

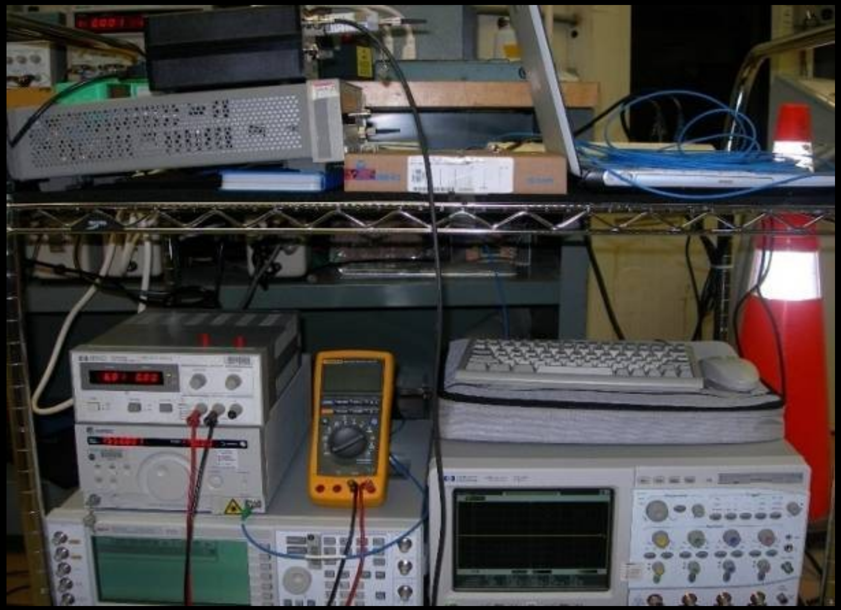
Fiber Laser Activities

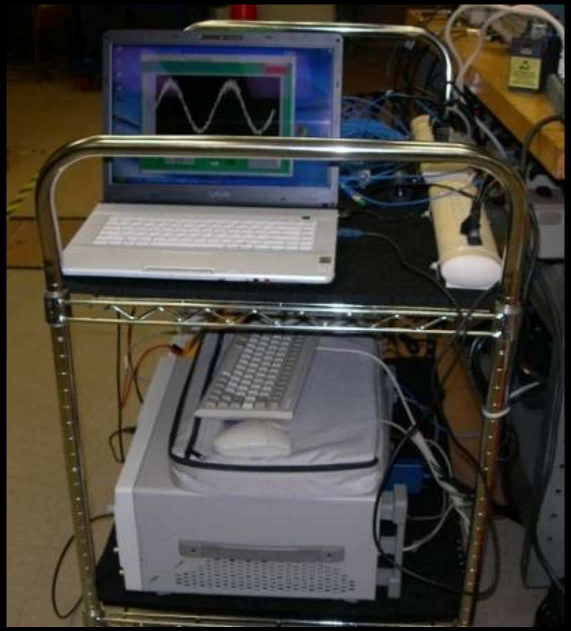
- **Remote sensing & high-bandwidth communication**
  - **Physical sensing (altimetry, ranging, 3D LIDAR)**
  - **Chemical sensing**

- **Investigation of fiber laser systems and components to raise / evaluate technology readiness level (TRL)**
  - **Confidence for future mission**
  - **Part of NASA Electronic Parts and Packaging (NEPP) http://nepp.nasa.gov**

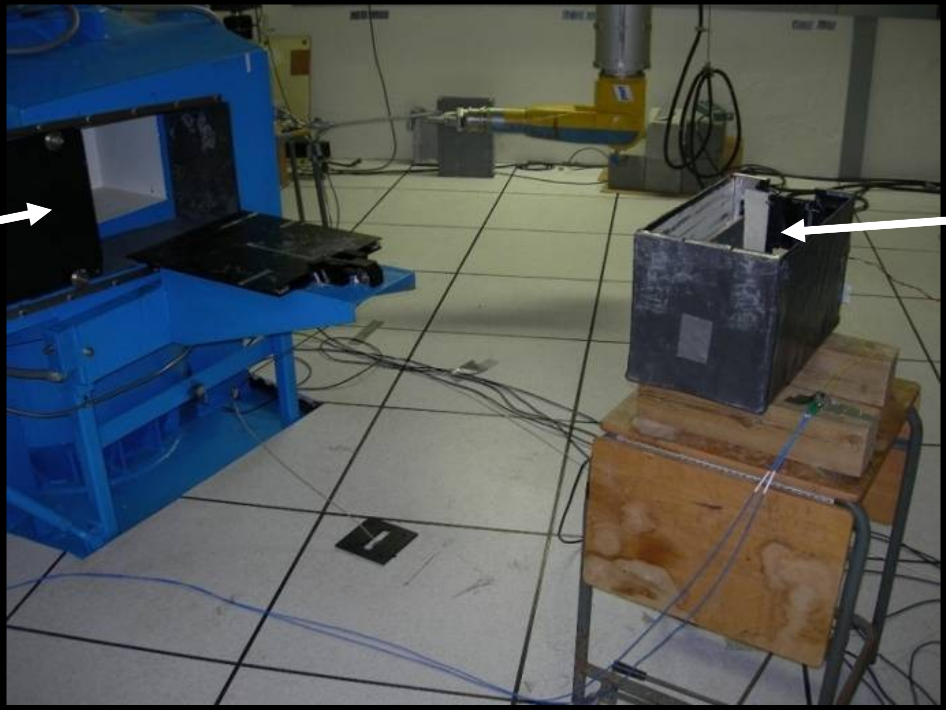
- **Fiber laser focus areas**
  - **Source / transmitter**
  - **Modulation**

Gamma Radiation Testing





Co^{60} Source



Modulator