1st ESA-NASA Working Meeting on Optoelectronics: "Fiber Optic System Technologies in Space"

5th & 6th of October 2005

Einstein Hall, ESTEC/ESA, Noordwijk, The Netherlands

Overview of Usage and Testing of Laser Components in Space Environments Survey 2005

Suzzanne Falvey
Northrop Grumman

Lee Thienel
Jackson and Tull

NORTHROP GRUMMAN

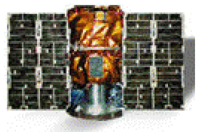
AIR FORCE RESEARCH LABORATORY

JACKSON AND TULL

Lasers and Fibers are Currently Used in Space

ICESat

SAMPEX



EOS

Key: Current / ***Future***

Space Qualified Lasers

Altimeters / Rangers
- GLAS / ICESat (LEO)
- ***LOLA (Moon)***
- MLA (Mercury)
- MOLA (Mars)
- NEAR (Eros)
- ***SIM (LEO)***
- TES (LEO)
- ***VCL/MBLA (LEO)***

Test Beds
- DSPSE (PEO)
- LDEF (LEO)
- MPTB (HEO)
- XTE (LEO)

Communications
- ETS-VI (GTO)
- HST (LEO)
- ISS (LEO)
- ***LCDE/ISS (LEO)***
- MAP (L2)
- MLCD (Mars)
- SAMPEX (PEO)
- SOLACOS (LEO, GEO)
- ***TSAT (GEO)***

LIDARS
- ***CALIPSO (LEO)***
- Clementine (PEO)
- GLAS (LEO)
- LITE (LEO)
- MLS (PEO)
- ***VCL (LEO)***

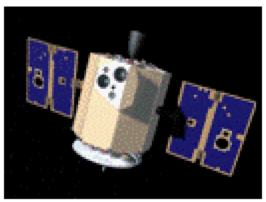
Gyroscopes
- Clementine-DSPSE (PEO)
- ***MEDSAT (GSO)***
- RXTE (LEO)

Fiber Lasers
- STS-95, 105,114/LCS (LEO)
- ***ESSP/††, CSA/††***
- ***HRVM (LEO)††***

†† indicates that discussion has been found, but no commitment has been made

MGS MOLA

XTE



Clementine

HST

NEAR

LDEF

Successful Implementations of Lasers in Space and Failures (Lessons Learned) were Surveyed

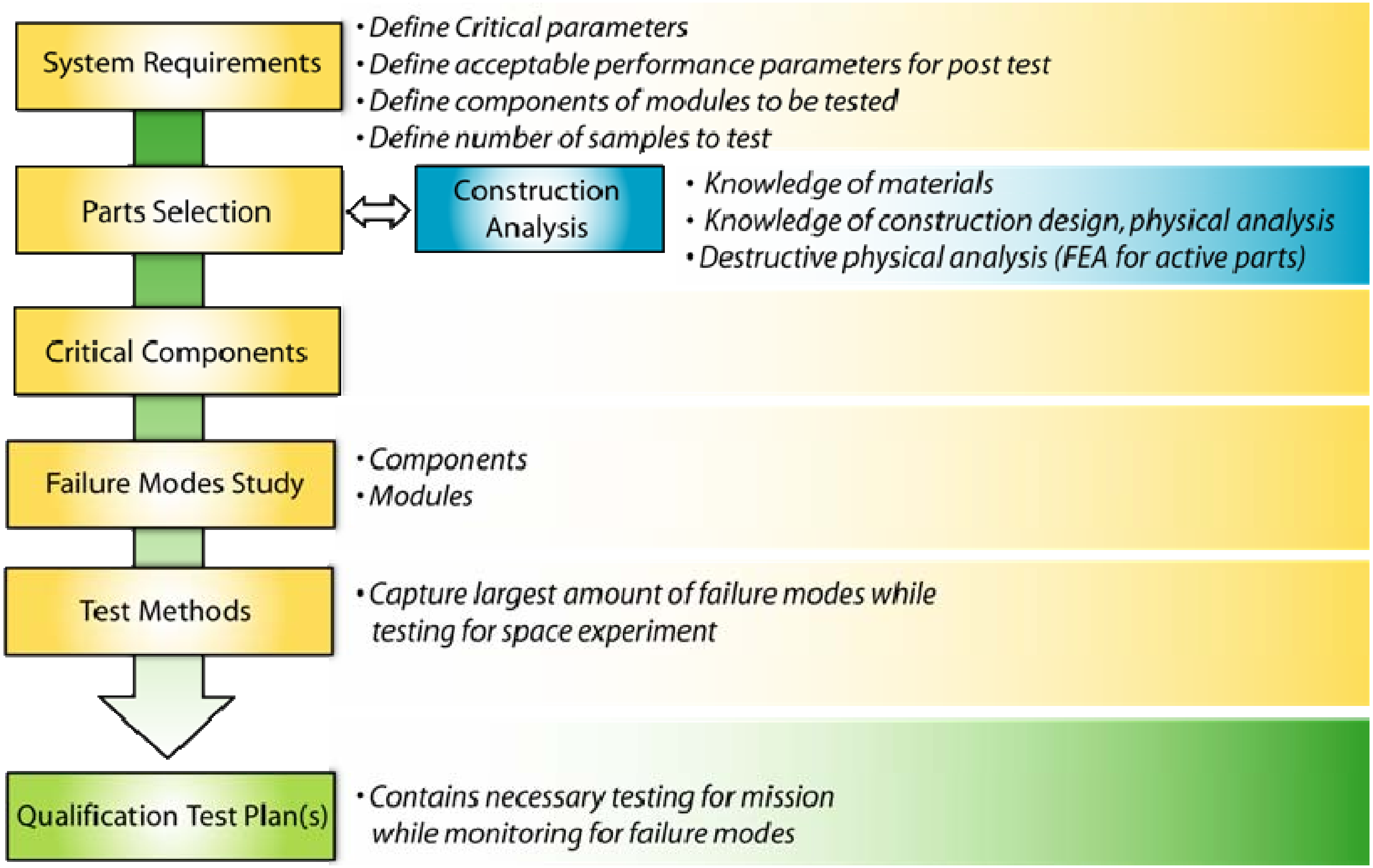
Background Survey of Laser Systems in Space

- Survey of space qualifying laser systems performed May 2005
  - All information freely accessible to the public were surveyed and reviewed
  - Concentrated on past 12 years
  - Includes fiber laser systems and components
- Surveyed >350 Articles in Bibliography
- Interviewed personnel at DOD, NASA, Aerospace, and other experts
- Telcordia, DOD, NASA, and other standards reviewed for space applications

Survey Results Grouped into Five Categories

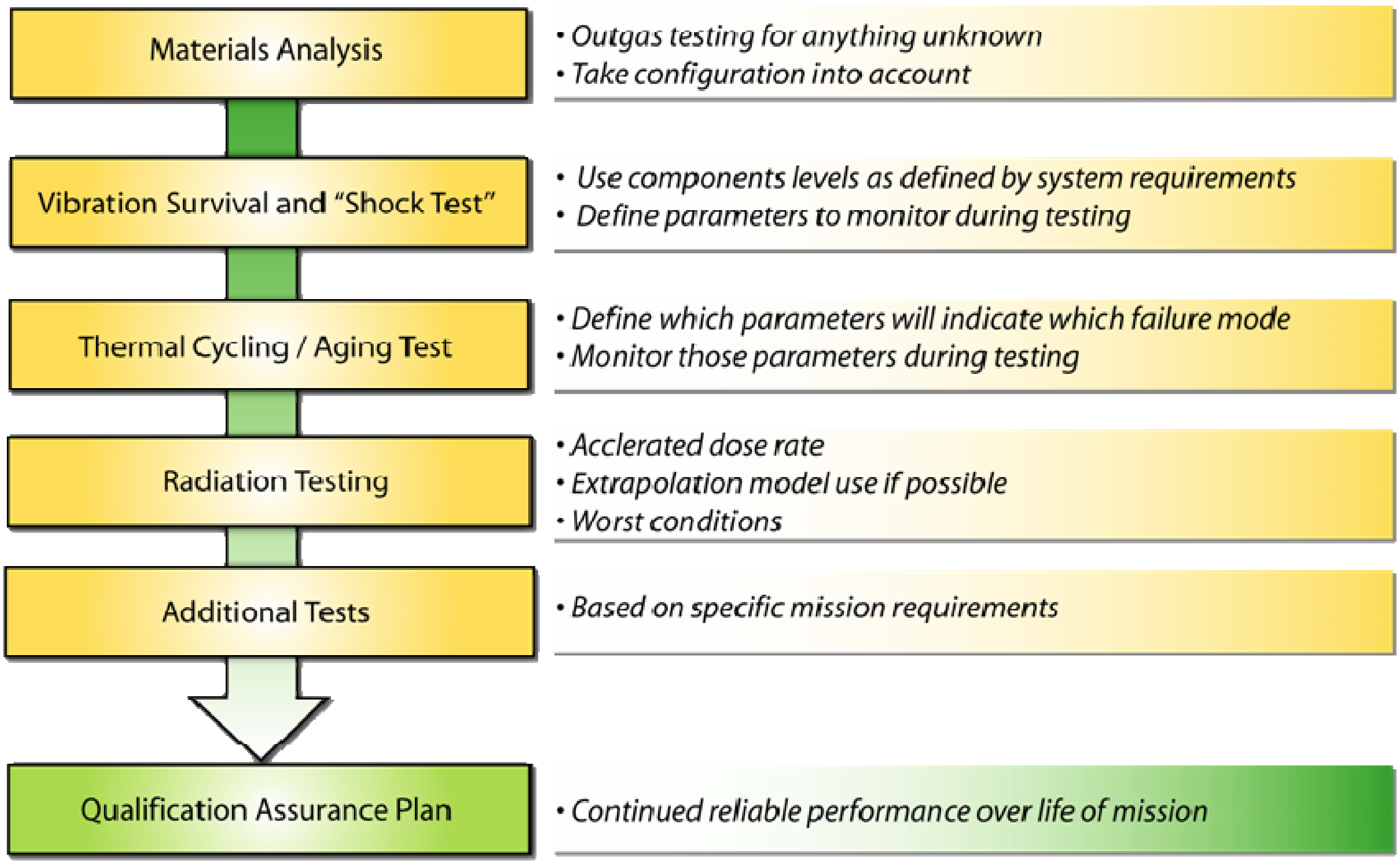
Environment Definitions	***Summarizes the specifications for space flight in an LEO; including radiation, thermal, vibration, and electrical.***
Space Qualification	***Summarizes current specifications and procedures for qualification of laser system components for space flight. Interviews with personnel at DoD, NASA, and others with experience in the area provide valuable background information.***
Standards / Test Methods	***Discusses the types of tests performed and needed for space qualification of laser components, modules, and systems.***
Failures / Lessons Learned	***Summarizes just what title suggests, for the analysis done for on-orbit GLAS instrument and other space-flight laser systems, to aid in future assessments and definition of space qualification protocols.***
Components	***Discusses the environmental testing results for laser components, modules, and systems, and identifies areas of concern for component tests that have not been performed or results that effect the development of a space qualification protocol.***

COTS Technology Assurance Approach for Space Flight*



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

Space Flight Qualification*



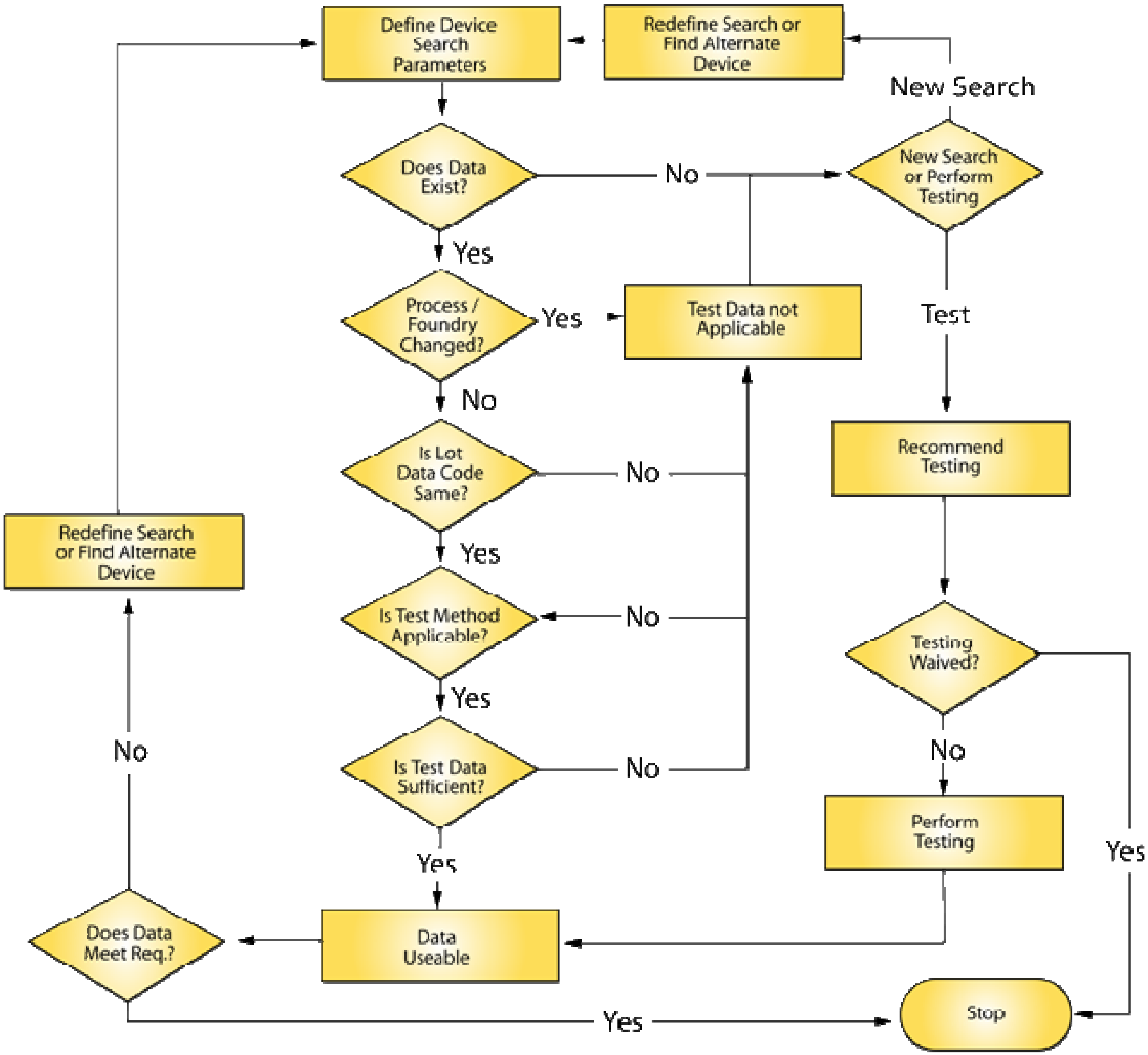
* *Photonic Components for Space Systems*, M. Ott, Presentation for Advanced Microelectronics and Photonics for Satellites Conference, 23 June 2004.

Standards and Test Methods

- Ground Testing for Space Qualification
  - Laboratory conditions significantly different from actual conditions
  - Test for worst case on ground to assure space reliability and survivability
- Always Perform Materials Analysis First
  - Reduced cost and schedule of overall tests
  - Understand mechanisms for failures
    - Aids in design of tests
- Combine Tests When Possible
  - Reduced costs
  - Compounded failure mechanisms

Don't Make Requirements Harder than They Need to Be

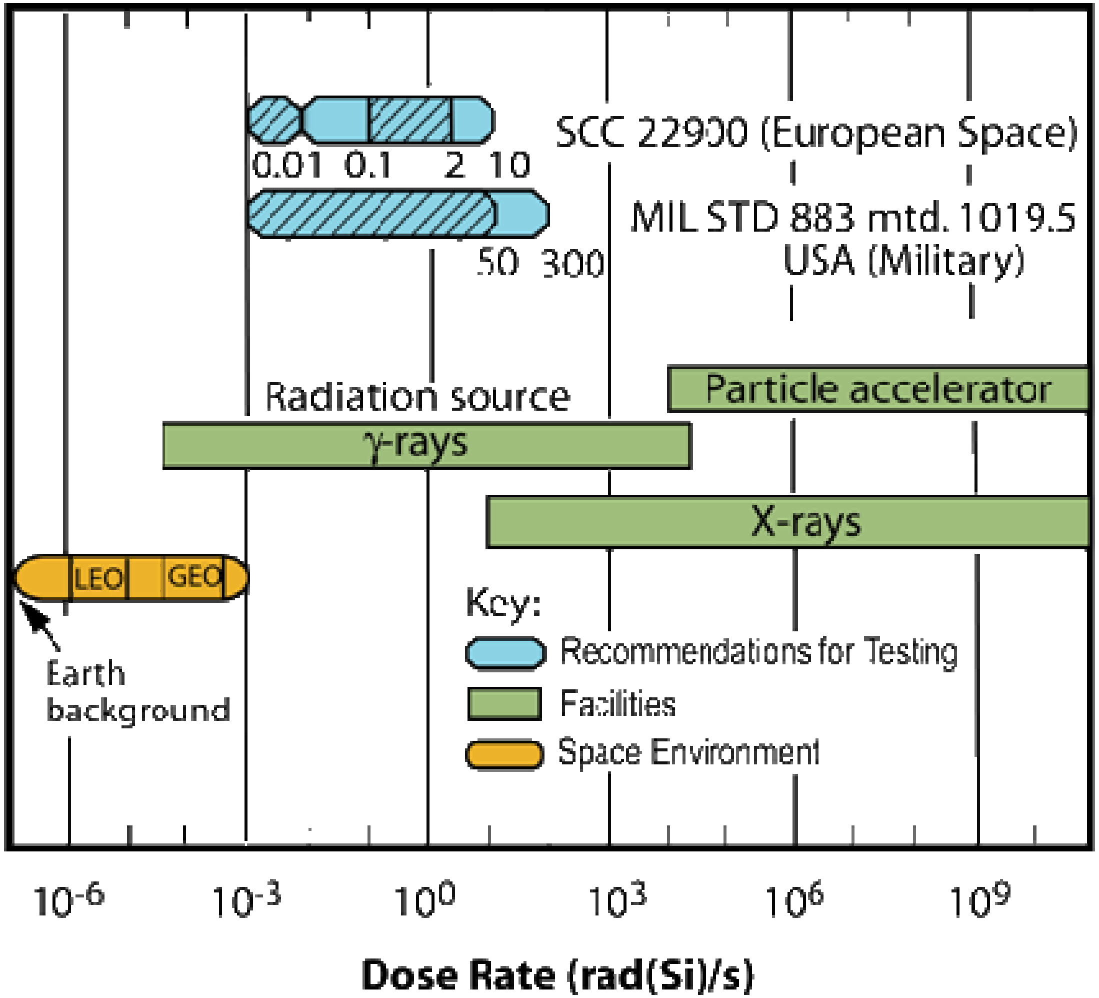
Materials Analysis Data Flow Example*



* *Space Radiation Environments and Effects*, J. Howard, Bright Light TIM #1, Presentation to AFRL, Mar 2005

Radiation Sources and Dose Rates – TID*

- **Laboratory Dose Rates are Significantly Higher than Actual Space Dose Rates**
- **Testing According to Test Standards Gives Conservative Estimates of Devices TID Sensitivity**



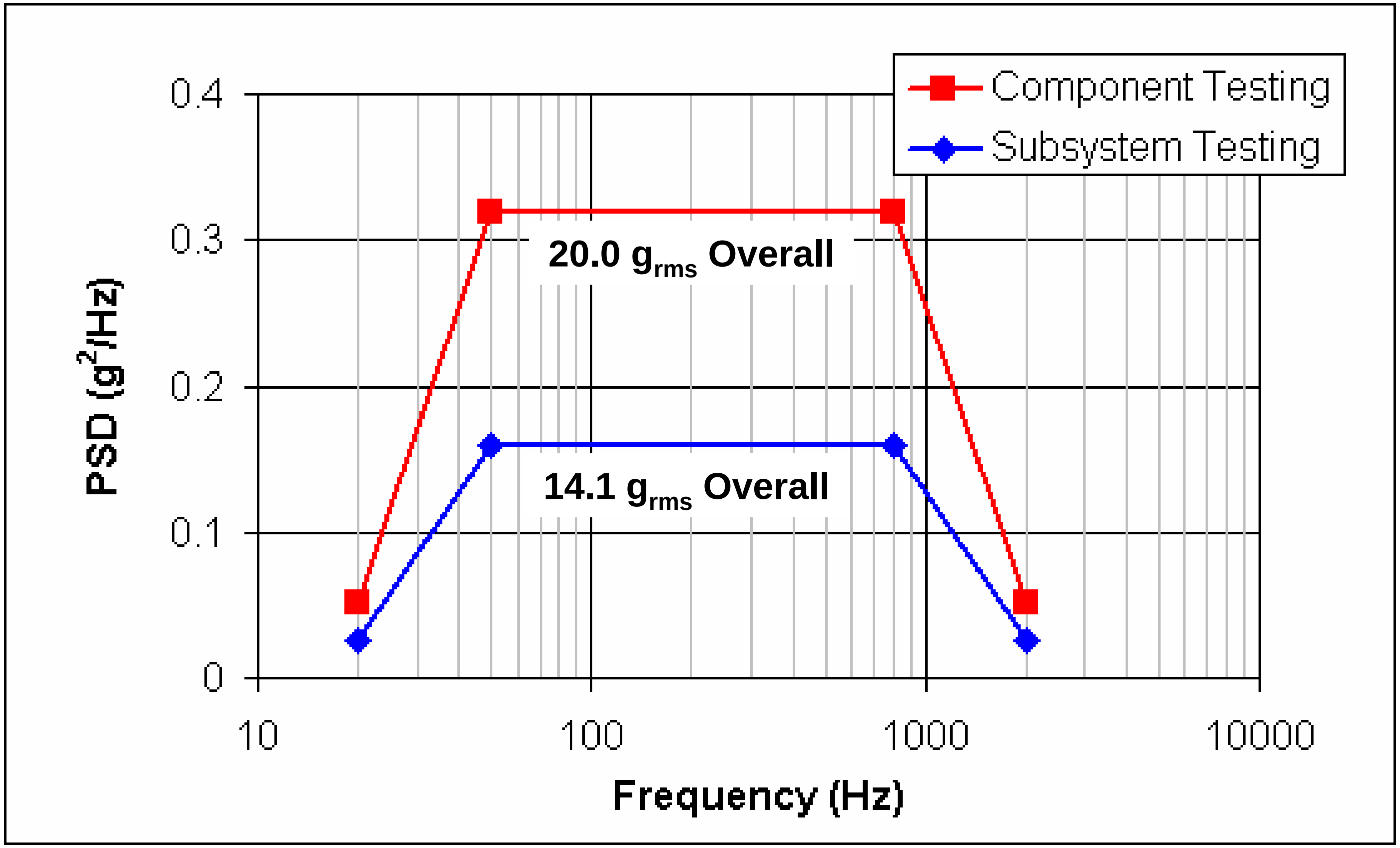
* *Radiation Hardness Assurance (RHA) for Space Systems, Presentation*, C. Poivey, Nuclear and Space Radiation Effects Conference, 15-19 July 2002

LEO System Thermal Testing Limits*

Parameter	Value	Units	Comments
Interior			Controlled environment
Thermal Vacuum	10^{-5}	Torr	
Extreme Temperatures	-10 to +55	°C	Minimum 20 min dwell at extremes
Thermal Cycling	12	cycles	2 °C/min ramp rate
Humidity, Relative	30 to 70	%	Ground testing
Exterior			Uncontrolled environment
Thermal Vacuum	10^{-5}	Torr	
Extreme Temperatures	-65 to +125	°C	20 min dwell at extremes
Thermal Cycling	12	cycles	2 °C/min ramp rate

* *The Effects of Space Environments on Electronic Components*, M. Petkov, NASA JPL, Jan 2003, and *Environmental Conditions for Space Flight Hardware – A Survey*, J. Plante, B. Lee, NEPP Web Article, Nov 2004

Vibration Profile Testing Levels*



3 minutes per axis, tested in x, y, and z.

* *Reliability of Optical Modulators for Space Flight Environments*, M. Ott, J. Vela, NASA Parts and Packaging Program, IPPAQ Task Report, Oct 2002, and *Validation of Commercial Fiber Optic Components for Aerospace Environments*, M. Ott, Presentation given at the 12th SPIE International Symposium on Smart Structures and Materials, Mar 2005

Many Test Methods have been Established

- Telecommunications Industries Association (TIA) Testing Methods Widely Accepted and Available
- NASA/GFSC Adapts Existing Test Methods
  - Utilizes TIA testing methods
  - Recommends Telcordia standards
  - Modifies existing methods for specific mission
    - TIA, MIL, IEEE, Telcordia, DOD, GSFC, IEC, ANSI, ASTM, etc.
  - Develops internal methods where none exists
- There is Consistency in Test Philosophies Across Agencies
  - Government (NASA/GSFC, NASA/JPL, NASA/LRC)
  - Military (Air Force, Navy, DOD)
  - Industry (Aerospace, Coherent Technologies, Fibertek, Northrop Grumman, Sandia National Labs)

Passive Components Test Methods Readily Available
Active Components Test Methods are NOT

Example NASA vs. Telcordia Test Requirements*

- **Due to the usage of MIL-STD-883 in Telcordia specifications, the random vibration environmental parameters and duration are of greater intensity than is required for space flight launch vehicles.**

	NASA Requirements		Telcordia Requirements
Vibration Testing	Vibration conducted on each of three areas	3 minutes / axis	20-2,000 Hz min / cycle
	Frequency (Hz)	Protoflight Level	
	20	$0.052\ g^2$ / Hz	
	20-50	+6 dB / Octave	
	50-800	$0.32\ g^2$ / Hz	
	800-2000	-6 dB / Octave	20G 4 cycles / axis
	2000	$0.52\ g^2$ / Hz	
	Overall	20.0 grms	
Thermal Cycling Testing	-20°C / +85°C, 30 cycles for pass / fail, 42 cycles for info		-40°C / + 70°C, 100 cycles for pass / fail, 500 cycles for info

Don’t Make Requirements Harder than They Need to Be

* *Reliability of Optical Fiber Modulators for Space Flight Environments*, M. Ott, et al, NASA Parts and Packaging Program Report, Electronic Parts Project, IPPAQ Task Report, October 2002.

Space Environment Hazards for Typical Orbits*

Space Hazard	Spacecraft Charging		Single-event Effects			Total Radiation Dose		Surface Degradation		Plasma Inter-ference with communications	
Specific Cause	Surface	Internal	Cosmic Rays	Trapped Radia-tion	Solar Particle	Trapped Radia-tion	Solar Particle	Ion Sputter-ing	O^+ Erosion	Scintil-lation	Wave Refrac-tion
LEO<60°	Not applicable	Not applicable	Relevant	Important	Not applicable	Important	Relevant	Relevant	Important	Important	Important
LEO>60°	Relevant	Not applicable	Important	Important	Important	Important	Relevant	Relevant	Important	Important	Important
MEO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
GPS	Important	Important	Important	Not applicable	Important	Important	Important	Relevant	Not applicable	Important	Important
GTO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
GEO	Important	Important	Important	Not applicable	Important	Important	Important	Relevant	Not applicable	Important	Important
HEO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
Inter-planetary	Not applicable	Not applicable	Important	Not applicable	Important	Not applicable	Important	Relevant	Not applicable	Relevant	Relevant

Important (red) Relevant (green) Not applicable (yellow)

Space environment hazards for typical orbits. Key : LEO<60° --- low Earth orbit less than 60 degrees incination, LEO>60° ---low Earth orbit, more than 60 degrees incination, MEO ---medium Earth orbit, GPS ---Global Positioning System satellite orbit, GTO ---geosynchronous transfer orbit, GEO--- geo-synchronous orbit, HEO ---highly elliptical orbit, O^+ --- atomic oxygen.

* *Radiation in the Space Environment*, Crosslink®, the Aerospace Corporation Magazine, Vol. 4, No.2, 2003

Sensitive Parameters

Example of Sensitive Parameters in Photonic Devices
(which are likely to be affected by one or more environmental tests)

Device Type	Sensitive Parameters
Optocouplers	Current transfer ratio
Fiber Optics	Transmissivity, polarization
LED	Light output
Laser Diode	Light output (efficiency), wavelength shift, threshold current shift, facet damage
AO & EO Modulators (Inorganic)	Refractive index, increased absorption, bandwidth, diffraction efficiency, coupling
AO & EO Modulators (Organic)	Increased absorption, conductivity changes, EO coefficient, SHG
Optical Fiber Modulators	Index of refraction
PIN Photodiodes	Increase in dark current
Waveguides	Transmissivity, absorption, polarization

Failure Modes and Mechanisms (1 of 2)

Component	Test	Mode / Mechanism
Fiber Optic Connector	Cable/Fiber Tension, Flex, Twist	Fiber Failure, Assembly Damage
	Vibration/Shock	Fiber End-face Damage, Assembly Damage
	Mating Durability	Fiber End-face Damage, Assembly Damage, Broken Sleeve
	Temperature/Humidity	Fiber Failure, Fiber Pistoning, Env/mech degradation of Assembly Materials, Fiber Withdrawal, Adhesive Degradation
Fiber Optic Splices	Cable/Fiber Tension, Flex, Twist	Fiber Failure, Assembly Damage
	Vibration/Shock	Fiber End-face Damage, Assembly Damage
	Temperature/Humidity	Fiber Failure, Fiber Pistoning, Env./mech. Degradation of Assembly Materials, Degradation, Moisture Absorption, Particulate Occlusion of Index Match Medium, Adhesive Degradation
Fiber Optic Cable Assemblies	Thermal Cycling	Material Changes Attenuation, Cold Temp Attenuation, Materials Shrinkage Attenuation, Fiber Exposure, Cracking of Fiber
	Vibration (Survival)	Cracking of Fiber and crack propagation
	TID (Attenuation)	Radiation Induced Effects
	Electron (Scintillation, SEE)	Radiation Induced Effects
Optocouplers	Radiation Hardness Assurance	Displacement Damage, Device Degradation
AO & EO Modulators	Radiation Testing	Thermooptic and Ionic Induced Refractive Index Changes, Increased Absorption

Failure Modes and Mechanisms (2 of 2)

Component	Test	Mode / Mechanism
Optical Fiber Modulators	Raised Thermal Operating Temperature	DC Drift, Hydrogen Diffusion
	Thermal Cycling	Fiber Buckling, Break, Material Expansion (OTE) Mismatching
	Vibration Testing	Fiber Buckling, Break
	Increased Optical Power	Degradation of Coupling Material
Optical Fibers & Waveguides	Radiation Testing	Radiation-Induced Color Centers, Changes to Absorption
Fibers, lenses	Radiation Testing	Darkening in Passive Optical Components
Optoelectronics	Radiation Testing	Particle Induced Displacement Damage
Laser Diodes	Materials Analysis	Laser Bar Material Defect, Solder Creep/Mitig-ation, Solder De-bonding, Bond Wire Failure, Packaging Issues
	Thermal Cycling	Accelerated Aging
Light Emitting Diodes	Radiation Testing	Displacement Damage in Active Region, Excess Minority Carries, Decrease in Minority Carrier Lifetime, Nonradiative Recombination
Edge Emitting Laser Diodes	Radiation Testing	Displacement Damage in Active Region, Excess Minority Carriers, Decrease in Minority Carrier Lifetime, Nonradiative Recombination
Injection Laser Diodes	Proton Radiation	Displacement Damage

Lessons Learned

Component	Parameter	Lesson
Laser Diode Bars	Reliability, Lifetime	Inspect bars to ensure that any gold wire is not in contact with indium
Injection Laser Diodes	Damage Mitigation	Utilize recombination enhanced annealing
Transmitter	Optical Power[41]	Design with sufficient margin
Fiber Optic Receiver	Radiation Performance	SEU test a system with an application specific method
Solid State Recorders	Radiation Hazards	Utilize system level fault tolerance to mitigate SEU concerns
Receiver Diode	Proton Reactions	Understand physical SEU mechanisms
Flight System	Risk Management	Use a thorough test and qualification program
Fiber Optic System	Space Integration	Utilize standard interfaces to reduce system integration time
Laser Transmitter	Thermal Control	Modify thermal model to improve the accuracy of temperature predictions
Various	Spacecraft Charging	Conduct a spacecraft charging prevention analysis
Fiber Optic Cable	Outgassing	Conduct a materials analysis first
	Shrinkage	Perform thermal preconditioning
	ESD	Review respooling process
Support Electronics	SEU, SEE, TID, Latchup, etc. Tolerance	Utilize appropriately hardened technologies

Components Test Data Results

- A considerable amount of TID & SEU radiation test has been accumulated
- Other data scarce
  - Lasers are new to space
  - Fiber systems have emerging technologies
- Concern is for lack of data for new technologies
  - An NEPP Readiness Overview summarizes nicely the reliability concerns and issues for space flight environments of fiber laser components technology*

Component or Device	Radiation Data	Vibration Data	Thermal Data	Lifetime/ Reliability Data
Fibers, Optical	●		●	●
Fibers, Graded Index	●			
Fibers, Single Mode Optical	●			
Fibers, Polarization Maintaining	●			
Fibers, Double Clad				
Fiber Optic Cables	●	●	●	
Fiber Optic Couplers	●			
Fiber Amplifiers	●		●	●
Fiber Bragg Gratings	●			
Fiber Laser Scanner	●	●	●	
Fiber Gyroscopes	●	●	●	●
Fiber Sensors	●	●		
Fiber Optic Data Bus	●	●	●	●
Optical Link Devices	●			
Optical Isolators	●			
Optical Glasses	●	●		
Laser Diodes, Injection	●			
Laser Diodes, MQW	●		●	●
Laser Diodes, Semiconductor	●	●	●	●
Light Emitting Diodes	●		●	●
Laser, Nd:YAG		●	●	●
Lasers, Semiconductor	●			●
Lasers, VCSEL	●			
Modulators, AO & EO	●			
Optocouplers	●			
Photodiodes, APD	●			
Photodiodes, PIN	●		●	
Q-switch, Passive	●	●		●
Waveguide Couplers	●			

KEY:
Further Testing Needed; Data Exists; Dependent Testing Operational Use

* An ● in a cell indicates that data exists for this component

* *Fiber Laser Components, Technology Readiness Overview*, M. Ott, NASA Electronic Parts and Packaging Program, Electronic Parts Project Report, March 2003

Performance Risk Test Matrix

Component or Device	Radiation				Thermal								Vibration				Electrical	
	TID	DD	SEU	ELDRS	Internal	Vacuum	Extreme Temps	Thermal Cycling	External	Vacuum	Extreme Temps	Thermal Cycling	Sinusoidal	Random	Acoustic	Pyrotech.Shock	EMI	ESD
Attenuators	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low
Detectors	Medium	Medium	Medium	Medium	Low	Low	Low	Low	Low	Low	Low	Low	Medium	Medium	Medium	Medium	Medium	Medium
Fiber Amplifiers	High	High	High	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Fiber Bragg Gratings	Medium	Medium	Medium	Medium	High	High	High	High	High	High	High	High	High	High	High	High	Low	Low
Fiber Collimators, Termination	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low
Fiber Connectors, Termination	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	High	High	High	Low	Low
Fiber Optic Cables	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Fiber Optic Couplers	Medium	Medium	Medium	Medium	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Fiber Optic Data Bus	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Fiber Optic Splitters	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low
Fiber-Pump Combiners	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	Low	Low
Fibers, Doubled Clad	High	High	High	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low
Fibers, Undoped	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low
Filters	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low
Gating Electronics	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Glasses, Gain Medium	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Isolators, Fiber Coupled	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	High	High	High	Low	Low
Isolators, high power	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	High	High	High	Low	Low
Laser Diodes	High	High	High	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low
Light Emitting Diodes	Medium	Medium	Medium	Medium	Low	Low	Low	Low	Low	Low	Low	Low	Medium	Medium	Medium	Medium	Low	Low
Mirrors, Laser Coupling	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Modulators, AO & EO	Medium	Medium	Medium	Medium	High	High	High	High	High	High	High	High	High	High	High	High	Low	Low
Optical Glasses	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Optical Isolators	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	High	High	High	Low	Low
Optical Link Devices	Low	Low	Low	Low	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Optocouplers	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low
Photodiodes, APD, PIN	Low	Low	Low	Low	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low
Q-Switch, Passive	Low	Low	Low	Low	High	High	High	High	High	High	High	High	Low	Low	Low	Low	Low	Low
Seed Master Oscillator	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	Low	Low
Waveguide Couplers	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low

key:
- Low Risk
- Medium Risk
- High Risk

Conclusions

- Successful Implementations of Lasers in Space and Failures (Lessons Learned) Were Surveyed
- Actual Radiation Environment Encountered Depends on Altitude and Inclination of Orbit, Total Mission Life, and Assumptions Made About Solar Flares
- In Developing Standards and Test Methods for Space Qualification, Don't Make Requirements Harder Than They Need to Be
- Passive Components Test Methods Readily Available, Active Components Test Methods Are NOT
- Concern is for Lack of Data for New Technologies (Fiber Lasers)
- Many Components for Fiber Lasers Need to be Tested to Reduce Performance Risk

Acknowledgements

- Thanks to team members
  - Northrop Grumman
    - Sami Hendow, Burke Nelson, Cherise Baker, Marisol Buelow, Dr. Tim Clark, Pat Cavenee
  - Jackson and Tull
    - Joseph Marino, Dr. James Howard, Guy Robinson
  - Muniz Engineering
    - Melanie Ott
  - United States Air Force
    - Major Thomas Drape, Colonel Norman Anderson
- This project was sponsored by the USAF, AF Materiel Command, AFRL, 3550 Aberdeen SE, KAFB, NM 87117 with Jackson and Tull as the Prime Contractor, under contract number F29601-01-D-0078