

From the Lab to Space: Comments on Instrument Qualification

Carl Weimer
Ball Aerospace & Technologies Corporation
CU 5/2/2016



Agility to Innovate, Strength to Deliver

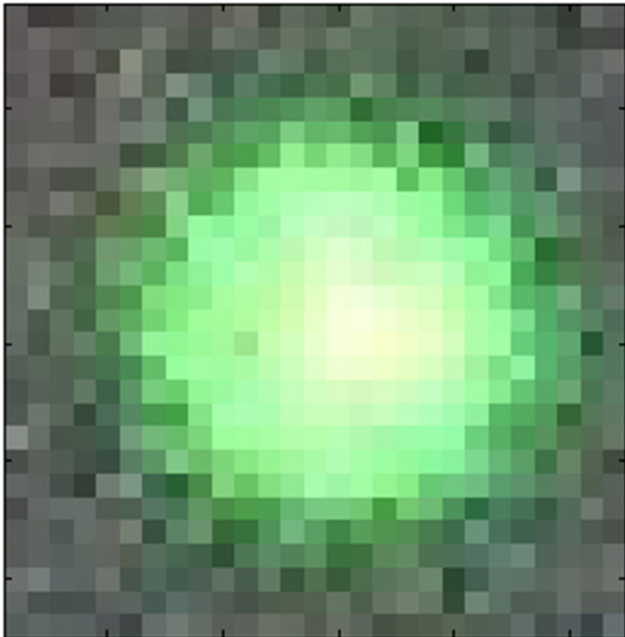


Ball Aerospace
& Technologies Corp.



Outline

- A Path from Lab to Space for NASA missions
- NASA and Technologies – Programmatic
- Space Environment – Challenges
- CALIPSO Mission
 - Examples of challenges for moving laser instruments to space



Pictures of the CALIPSO satellites laser beam taken looking up from Colorado.
Courtesy Emsley and Hendry



A Path from Lab to Space the NASA approach

Initial Steps:

- **Compelling Science is Defined**
 - Science should match NASA science objectives found in NRC Decadal Surveys for NASA Science Mission Directorate (SMD) , and other NASA internally generated roadmaps
 - The science can best be done, or requires that it be done in space
- **Mission Feasibility is Studied**
 - Mission Architecture defined and alternative approaches analyzed
 - Evaluation of a mission risks, complexity, maturity is completed
 - Cost Estimate performed

Intermediate Steps:

- **Mission is marketed to community**
 - Champions are critical to success
- **Instrument maturity relevant to space is advanced (any way possible)**
 - Focus is on key subsystems that haven't flown previously (usually viewed as "high risk")
 - "Advancing the Technology Readiness Level" (TRL)



Path to Space (continues)

Final Steps:

- **Complete Instrument/Mission Architecture**
- **Perform Trade Studies on Options with performance/cost in mind**
 - May need to descope science requirements to fit into costs
- **Disciplined flowdown of requirements from science to design**
- **Creation and implementation of a Qualification Plan**
 - Environmental Conditions for Launch and Orbit are defined
 - Detailed look at the risks to instrument success
 - Materials and Processes that are acceptable are defined - tension between COTS and Full traceability
 - Electronics Parts Program that matches the risk level is followed – Radiation is critical
 - Test Program created that matches the environmental conditions and helps address the risks
- **Qualification is expensive and time consuming**
 - Often small companies are doing the work, limited resources, SBIR a good approach
 - Most parts have not been studied, especially state-of-the-art parts



NASA Science Missions

- Risk tolerance of new technologies in different programs is an important element – cost growth is commonly blamed on new technologies
 - Higher Risk Acceptable (Technology Demonstrations – Low Cost - 1 Year Operations)
 - ❖ ISS missions (until 2024 at this point) – but no risk to astronauts is accepted
 - ❖ Nanosats/Cubesat/Smallsats
 - ❖ Secondary Payloads
 - ❖ Sounding rockets/sub-orbital
 - Lower Risk Needed (Focused Science Missions - Medium Cost – 3- 5 years Operations)
 - ❖ Science Missions competed and evaluated through the TMC Office
 - Compelling Science aligned with NASA objectives
 - Feasibility (Cost, Schedule, Risk, Technology Readiness, heritage) must be demonstrated
 - But note – only testing relevant to the space environment counts towards Feasibility
 - Talking about 1 – 3 year continuous, autonomous operation, after launch
 - Lowest Risk - (High Impact Science Missions - High Cost – 5- 10 Year Operations)
 - ❖ Prioritized in the NRC Decadal Surveys (ES 2007, AS 2010, PS 2013, Helio 2013)
 - ❖ Study period helps define mission, burn down risk



Examples taken from CALIPSO

- Joint US/French satellite funded in the Earth System Science Pathfinder program (medium risk) to study aerosols and clouds and their radiative impact to Earth
 - PI David Winker NASA LaRC
- Three instruments:
 - Dual-wavelength, polarization-sensitive lidar
 - Infrared Imaging Radiometer
 - Cloud camera
- 705 km orbit, Sun Synchronized, part of the A-Train of Satellites
- On-orbit 9½ years (3 year mission), still meeting requirements



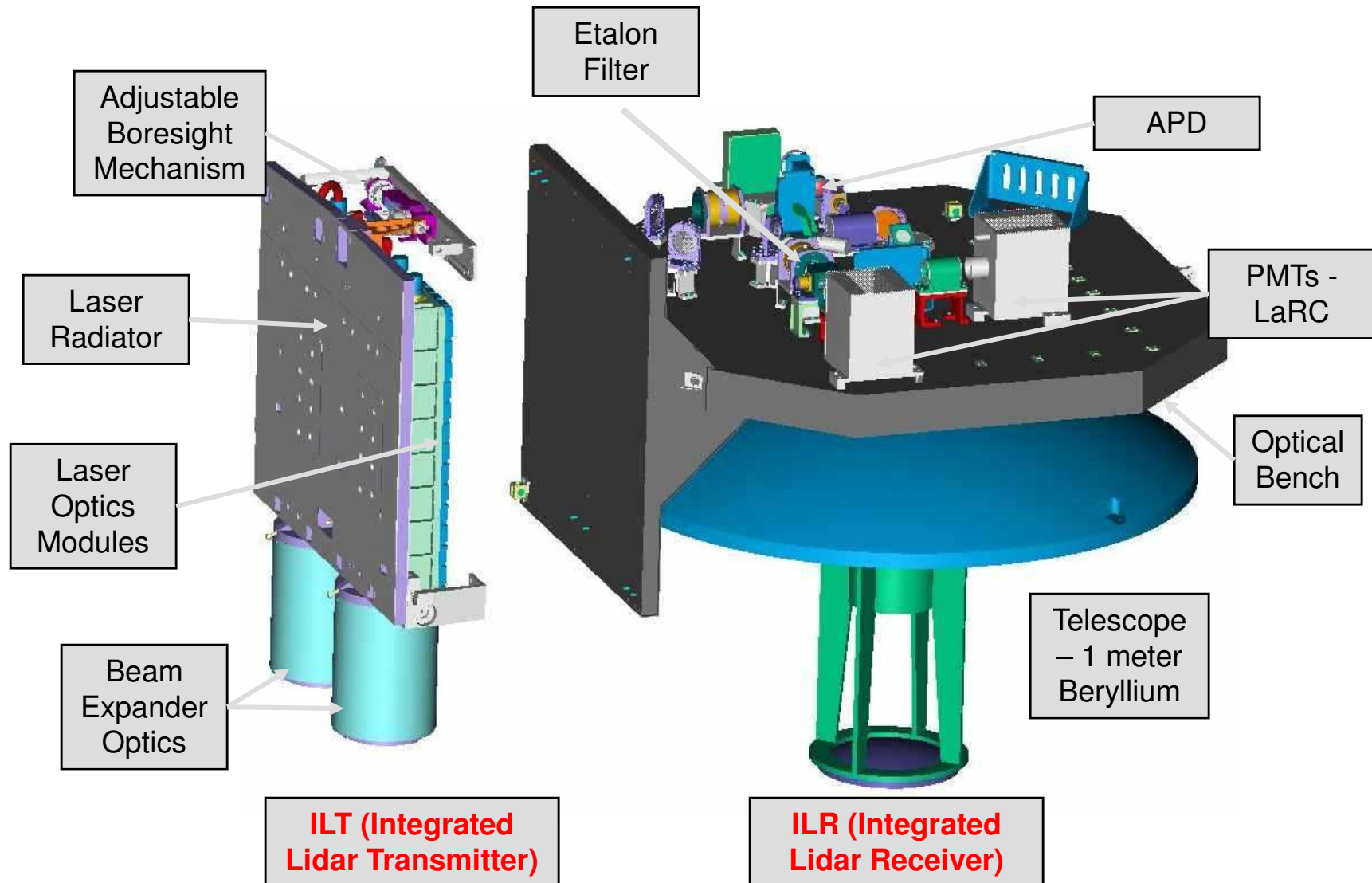


CALIPSO's Path to Space

- **Development of the compelling science associated with aerosol and cloud impact on Earth's radiation budget was done by broad group of researchers**
 - NASA LaRC's work on application of backscatter lidar to atmospheric characterization
 - Early weather satellites began cloud studies, followed by science satellites using limb sounders to study aerosols
- **Lidar demonstration missions were done on Shuttle**
 - Explored early Mission Architectures
 - Advanced Technology Readiness
 - Examples: LaRC (LITE); GSFC (Shuttle Laser Altimeters)
- **Champions developed an international team**
- **Key new technology for space – Q-switched, Diode-pumped Solid-State Lasers**
 - Deemed too high of risk by TMCO for an ESSP mission
 - Investment was made to build a lifetime unit to validate design and show full life
 - “Risk Reduction Laser” completed equivalent of a 3 year mission, is still being used today to help answer questions on extending the life of the mission



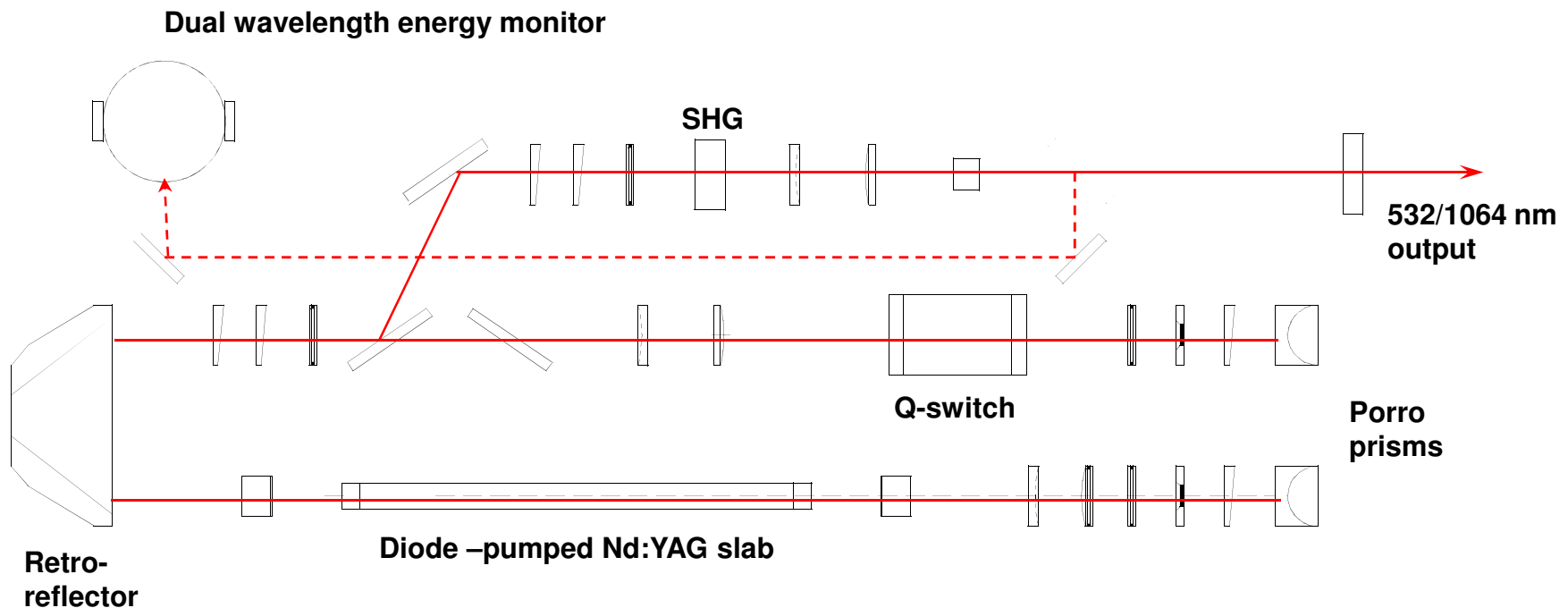
CALIOP Lidar on CALIPSO





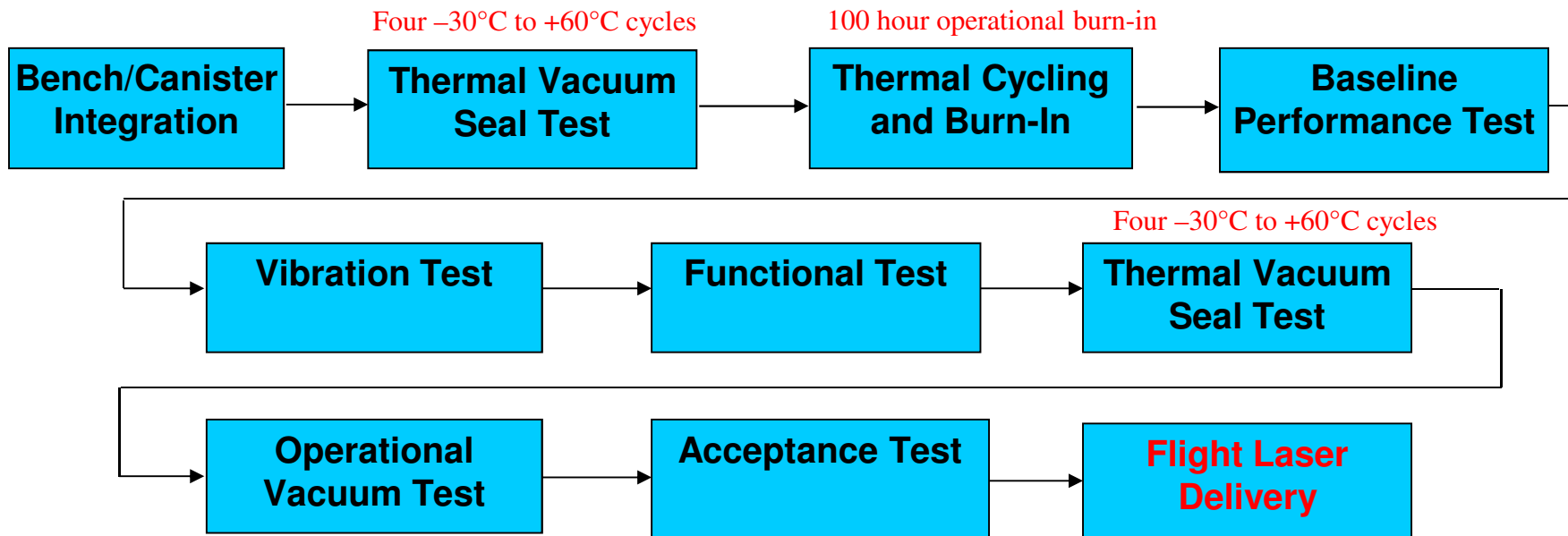
CALIPSO Laser Qualification - Example

- Diode - Pumped Nd:YAG, custom manufactured by Fibertek, with Ball and NASA
- Crossed Porro Prism optical cavity for alignment ruggedness
- Q-switched – KD*P Pockels Cell
- Second Harmonic Crystal - KTP
- 220 mJ (total) @ 20 Hz, 20 ns pulses
- Multi-TEM modes
- Lifetime laser was built and completed full lifetime test prior to flight build





Qualification Test Flow for Flight Laser



Response at Radiator Interface

X Axis		Y Axis		Z Axis	
Freq. (Hz)	ASD (g ² /Hz)	Freq. (Hz)	ASD (g ² /Hz)	Freq. (Hz)	ASD (g ² /Hz)
20	0.01	20	0.01	20	0.01
20-65	4.1 dB/oct	20-55	16.8 dB/oct	20-70	13.0 dB/oct
65-105	25.0 dB/oct	55-100	-13.9 dB/oct	70-100	-14.2 dB/oct
105-125	-46.5 dB/oct	100-800	-3.2 dB/oct	100-800	-4.4 dB/oct
125-450	0.18	800-2000	-2.3 dB/oct	800-2000	-2.3 dB/oct
450-800	-11.5 dB/oct				
800-2000	-2.3 dB/oct	Overall Grms:	10.67	Overall Grms:	11.58

Overall Grms:	12.12
---------------	-------

From Coasterpedia:
Highest load of a
roller coaster 6.3 g
– South Africa



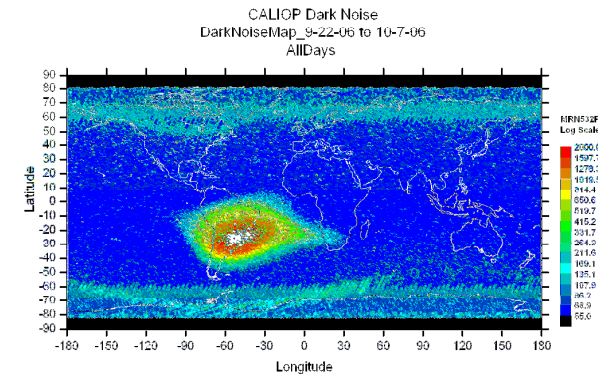
Some Lesson Learned from CALIPSO Laser development

- Use **mature laser technologies**
 - The cost and schedule constraints of a space-based lidar mission coupled with the logistic complications of any "routine" space mission provide ample opportunities for failure without even introducing a significant technology risk component.
- Use **alignment insensitive resonator designs**
 - Typical lidar boresight requirements tolerate $>100\ \mu\text{rad}$ raw beam wander
 - Many resonators exhibit significant power drop for $100\ \mu\text{rad}$ misalignment
- Develop and practice **stringent contamination control** procedures
 - The evolution of contaminants in an optical compartment is a one of the major long term failure mechanisms in space-based lasers
 - Contamination control procedures developed that combined traditional aerospace techniques with unique laser requirements and were validated with lifetime testing
- Operate all optical components at appropriately derated levels
 - Derating of optical components in lasers is less well defined than electrical and mechanical components
 - The laser diodes used to pump the Nd:YAG gain medium were run at peak optical powers derated by $>30\%$ of their design values
 - The power density in the Nd:YAG slab is $1/3$ the damage threshold. For all other optics the fluence/damage threshold ratio is $<1/4$
- Budget properly for the space-qualification of the electronics and software
 - The most programmatically difficult area for the CALIPSO laser transmitter was meeting the planned cost and schedule for building and qualifying electronics

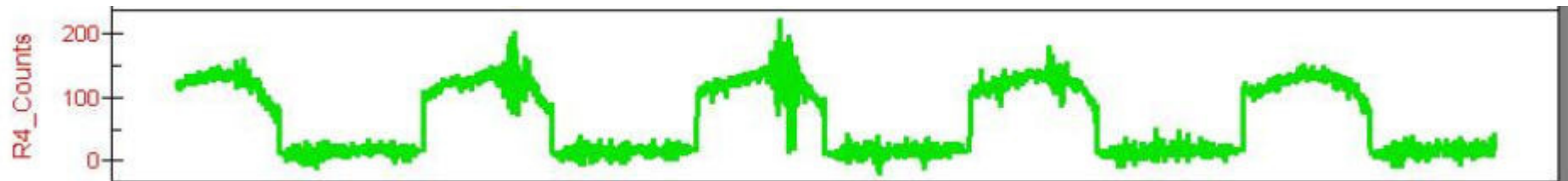


Impact of Radiation Environment - Detector Example

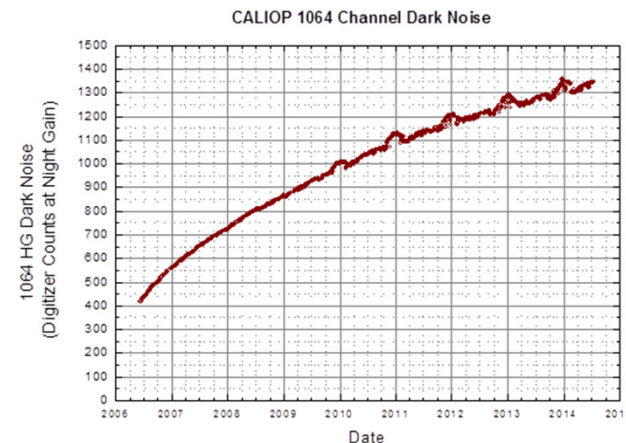
- CALIPSO uses both Photomultiplier tubes (PMT – 532 nm) and Silicon Avalanche Photodiodes (APD – 1064 nm)
- 705 km orbit takes the satellite through the South Atlantic Anomaly (SAA) where there is a higher flux of electrons
- No damage to PMTs but significant performance loss in SAA



Lidar signal at 532 from High Altitude for five orbits through SAA – Nighttime only



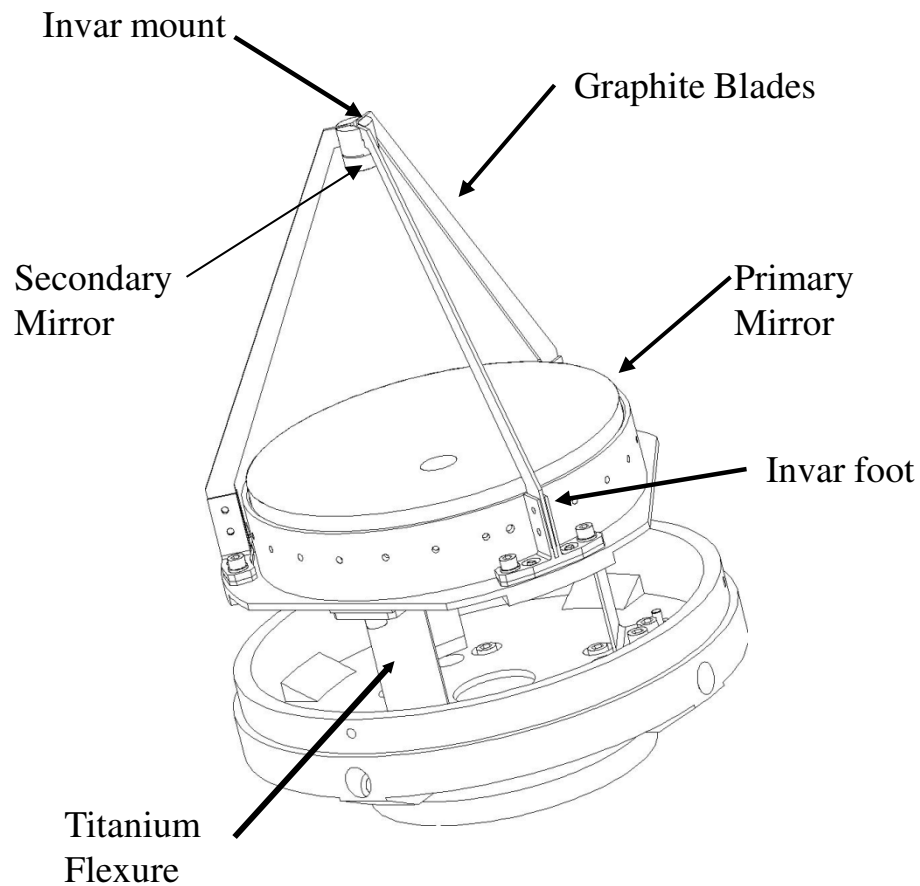
- The silicon APDs suffer proton displacement damage of the semiconductor leading to a permanent rise in their dark current over time





Impact of Launch Vibration – Beam Expander Example

■ BEO Lessons Learned



Total wt: ~5.5 lbs (with sunshade)

Mirrors

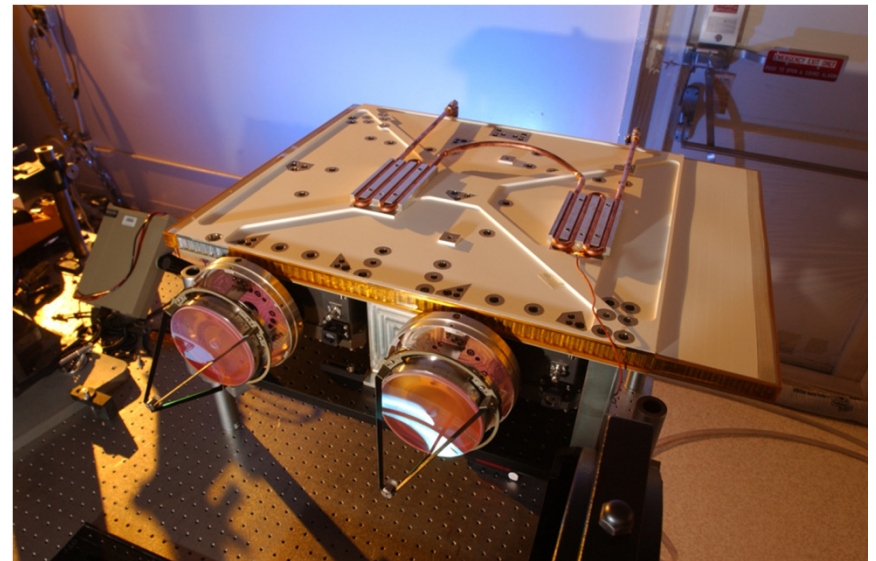
Zerodur substrates

Parabolic (Cassegrain)

$\lambda/20$ rms

Primary: 125 mm Clear Aperture, f/0.9

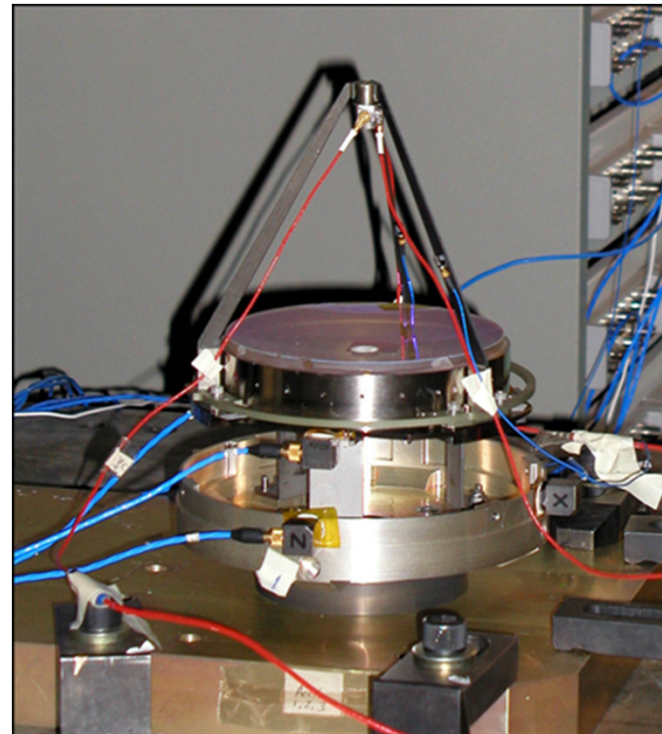
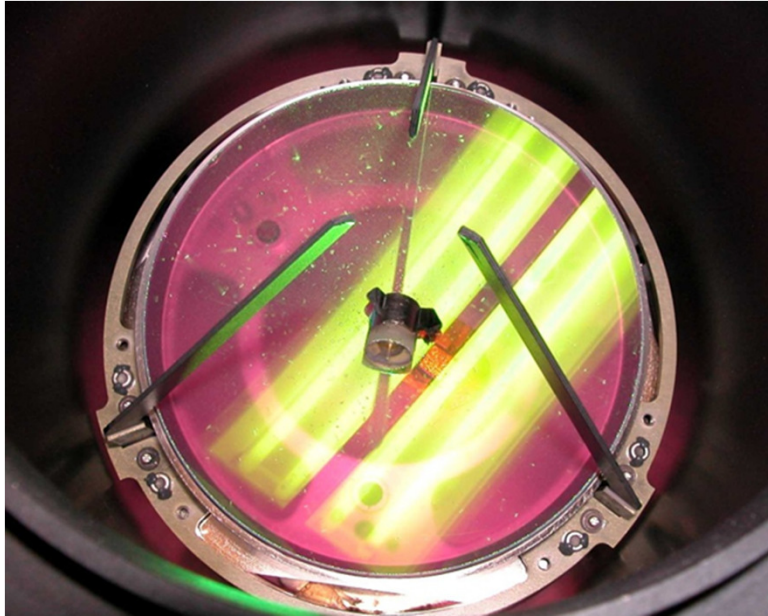
Secondary: 7 mm Clear Aperture, f/0.8





What Vibration Testing can do to precision optics

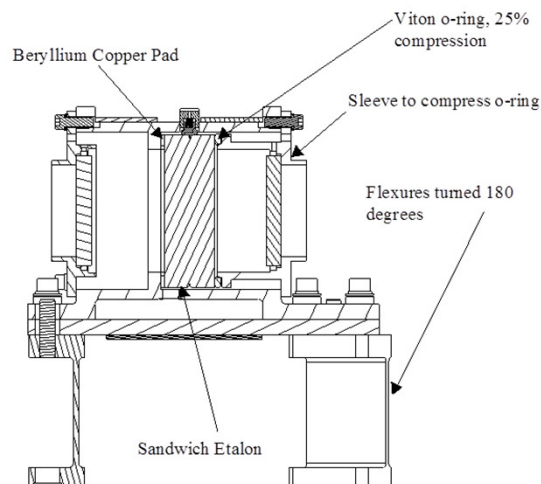
- No Plan (money) to build an Engineering Design Unit, so directly to flight
- Failed in vibration when it reached the full launch levels
- Rebuilt, retested as an EDU – identified five contributing factors to vibration failure
- Redesigned, rebuilt, retested and successful on-orbit



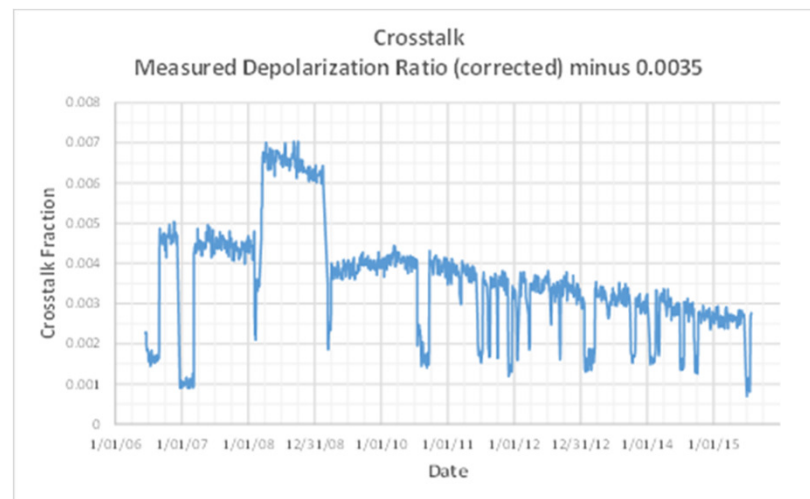


Impact of Thermal - Etalon Example

- Large “survival” temperature range (e.g. -30C to + 60C) is challenging for mounts, bonds, and materials with dissimilar CTEs
- Creating a mount that can handle the thermal extremes, vibration, and performance issues is a challenge to design, and to test
 - Solid Etalon in a “sandwich” configuration was used as a background light rejection filter
 - Etalon is 128 micron thick (between substrates), with a Finesse of 18, optically contacted
- CALIPSO’s total polarization crosstalk was required to be $< 1\%$ (.01)
 - Requirement was met, however instrument’s high performance can detect subtle effects
 - Results was dominated by mount induced stresses and hysteresis
 - Since the derived science requirement was met, no additional testing or effort expended



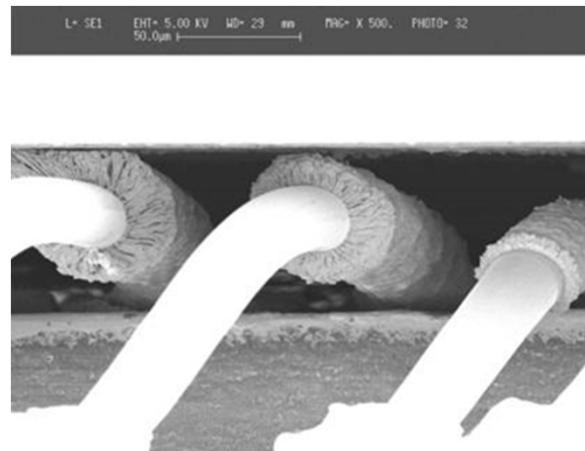
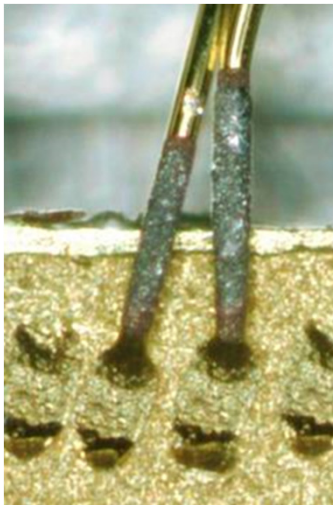
Graphite Bench





Impact of multi-year mission - Materials Example

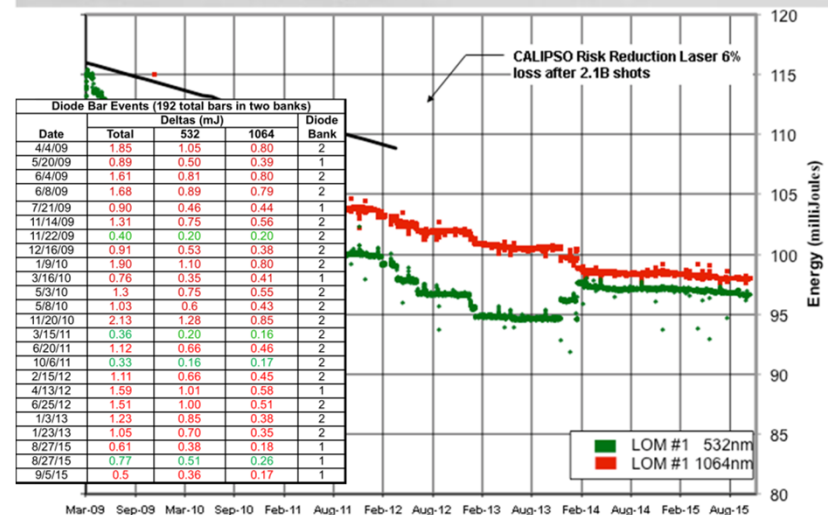
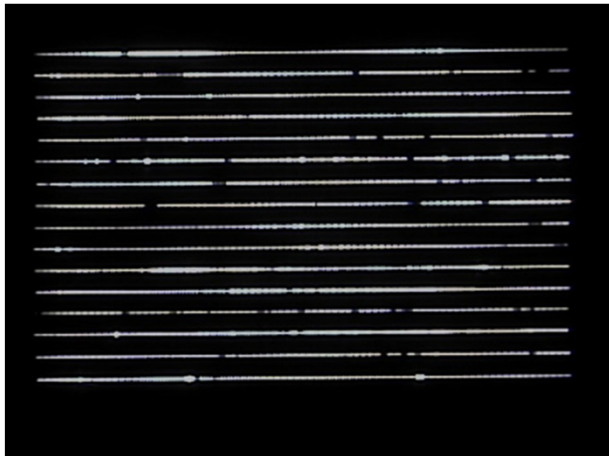
- **Gold Indide growth – killed ICESat’s first laser when their diode bars apparently suffered a cascading failure in its diode bars resulting from this effect combined with no derating of the current levels**
- **Diffusion of indium into gold creates gold indide, a brittle inter-metallic material**
- **At room temperatures this might take 2- 3 years before bond wire is totally transformed into the intermetallic compound resulting in loss of strength**





Impact of multi-year mission - Second Materials Example

- Tin whiskers can grow from solder under some conditions
- Can lead to shorts and burning of surfaces, including optical facets
- Observed in diode laser arrays leading prematurely to dead emitters and “bars”





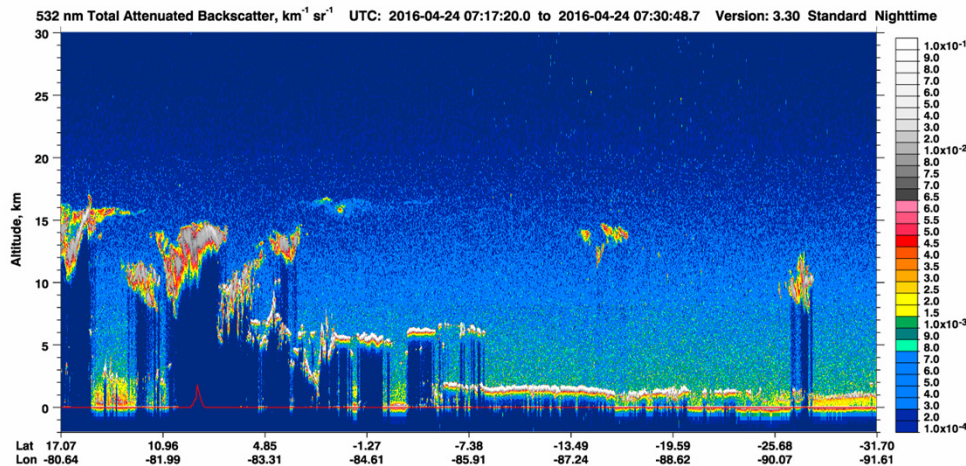
Suggestions

- **No path forward without compelling science that needs to be in space**
- **Critical to develop “reasonable” science requirements and goals, and a mission architecture with manageable complexity and within the budget**
- **Don’t overreach – take a disciplined path to space – Lab, EDU, Flight Technology demonstration (e.g. cubest, ISS, secondary payload), science mission**
 - Understand the risks, plan on how to reduce them to the level that is acceptable to the program level
 - Treat this as a path to “burn down” risk
- **Get the money to do the new subsystem testing needed for space**
 - Leverage heritage of what has gone before
 - Do realistic environmental testing for the space/launch environment
- **Materials and Process (M&P) Engineering is a critical contributor to success of packaging for space**
 - Parts Engineering (includes radiation analysis) is important for electronics,
 - Heritage for laser materials in space is not deep, extra effort is required
- **Laser based systems have had a spotty record of success in space, but following a disciplined approach will continue to succeed and enable new science**



Current Lidars/Laser Altimeters and Planned for Space

CALIPSO (532 nm/1064 nm Cloud/Aerosol)

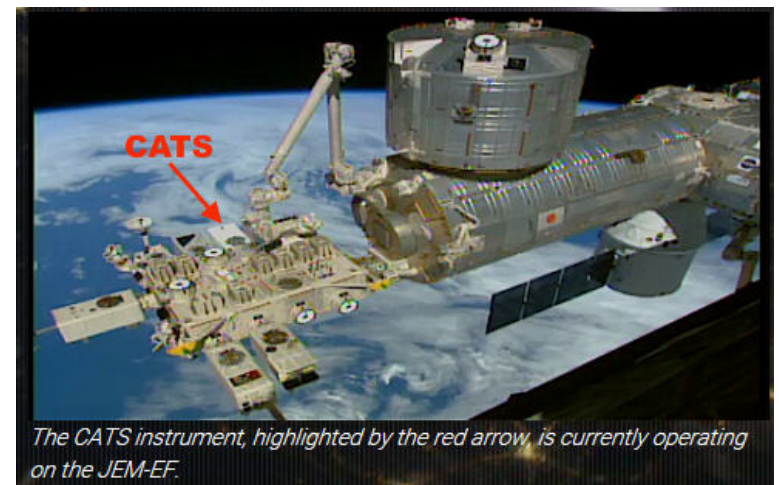


LOLA (1064 nm lunar mapping) (Kreslavsky 2013)



Currently on their way to space (over next 5 years)

- Raven (1550 nm, relative navigation)
- OSIRIS REx (relative navigation and surface mapping)
- ADM-Aeolus (355 nm, 3D Doppler Winds)
- EarthCare (355nm, HSRL Cloud/Aerosol)
- ICESat-II (532 nm, surface topography)
- GEDI (1064 nm, Forest Canopy)



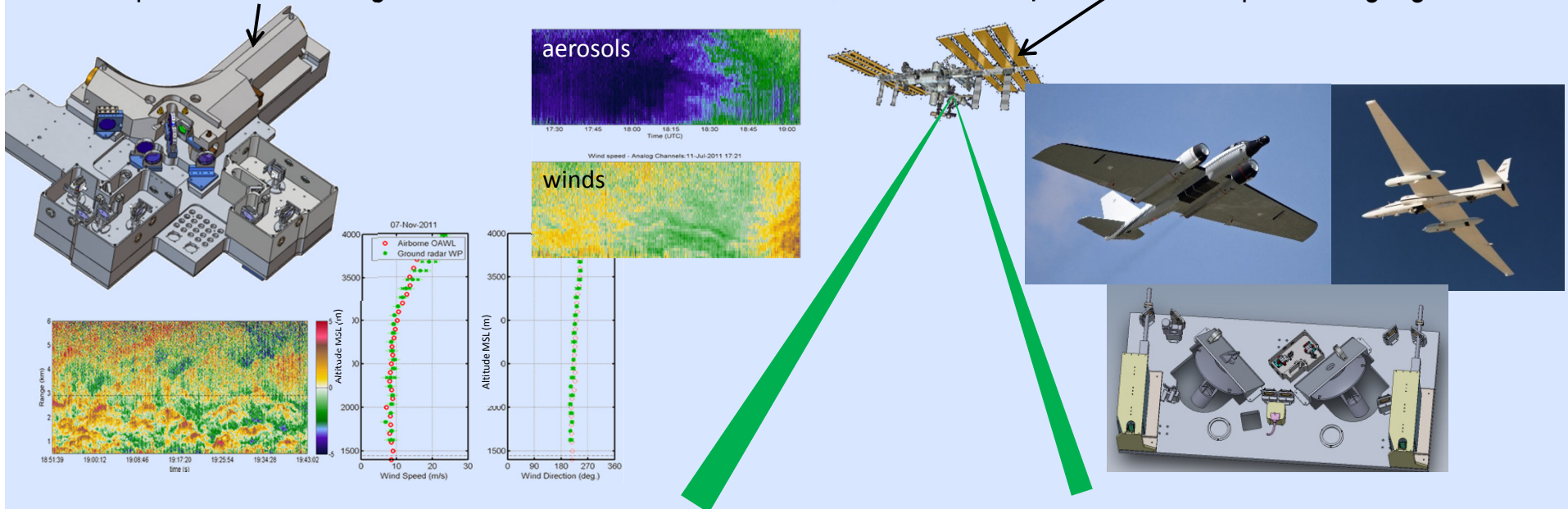
CATS-ISS (532/1064 nm Cloud/Aerosol) (McGill)



Evolution of an OAWL to Space Ball's Optical Autocovariance Wind Lidar

2013 ATHENA-OAWL Mission Proposal

1999-present: Ball design, build and test of OAWL receivers, mission concepts and retrieval/processing algorithms



2008-2012: OAWL IIP-07

- Breadboard system
- 355 nm only, 4x channels
- Single look 12" telescope
- Ground validation with NOAA Coherent system
- Autonomous flight tests on NASA WB-57

2012-2015: HOAWL ACT

- Breadboard System
- Demonstrate 532 nm wavelength channels & depolarization channels
- Total 10 channels
- HSRL Aerosol retrieval algorithms

2015-2017: ATHENA-OAWL Venture-Tech: GrOAWL

- Airborne demonstrator System (WB-57)
- 2-lasers = 400 Hz eff. PRF
- 4x 532 nm channels
- 2 looks, 2 telescopes to demonstrate geometry

2014-2017: HAWC-OAWL IIP

- HSRL Validation study with NCAR (2016)
- Two look airborne system (build on GrOAWL)
- Dual Wavelength + depol. Channels = 10x @ 400 Hz
- Update interferometer