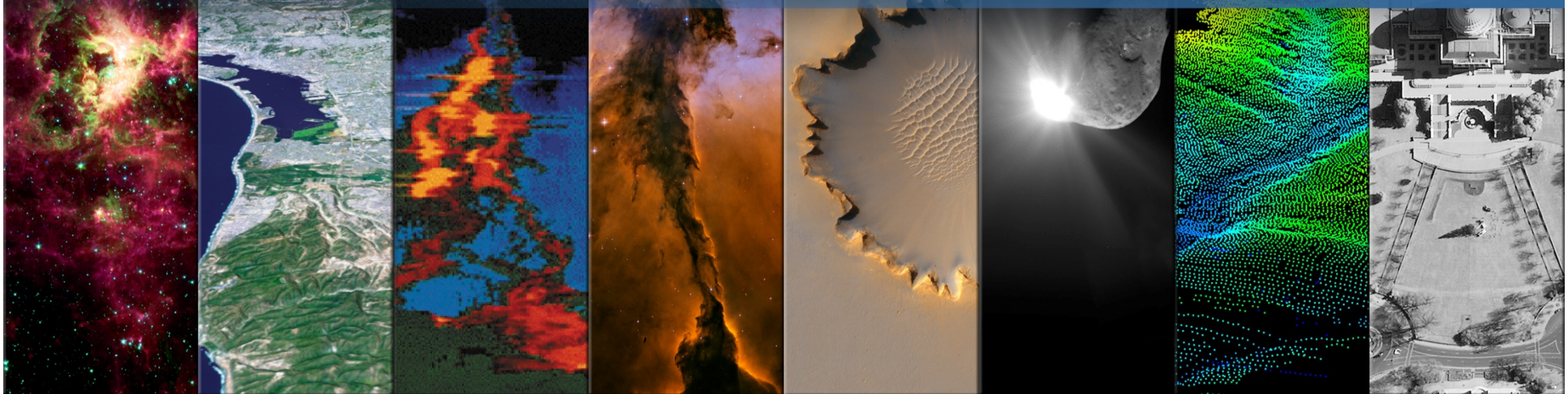
From the Lab to Space: Comments on Instrument Qualification

Dr. Carl Weimer
Ball Aerospace & Technologies Corporation

11/2/15 – KISS



Agility to Innovate, Strength to Deliver

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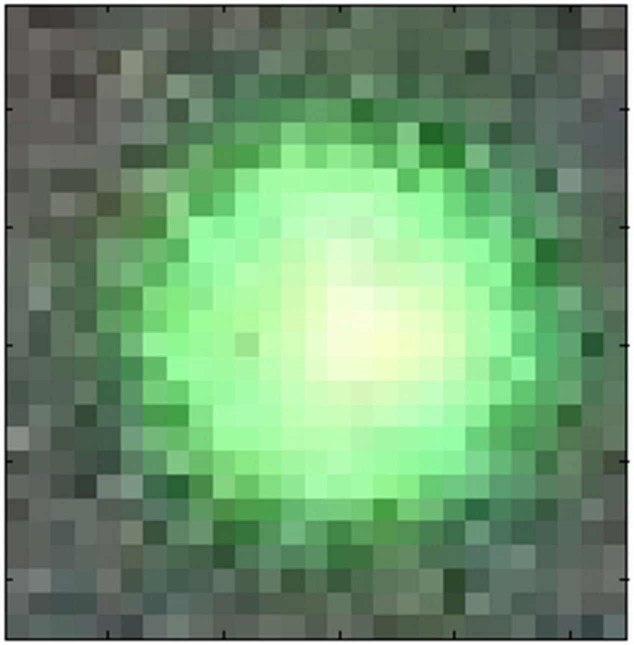
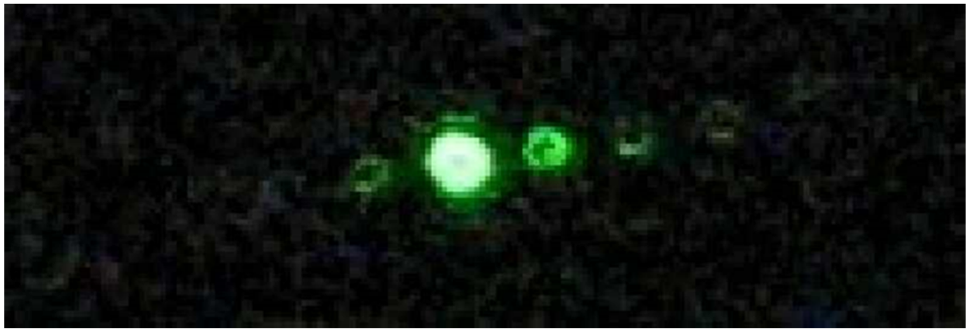
Outline

- 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

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- **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
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Intermediate Steps:

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  - 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**
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  - Environmental Conditions for Launch and Orbit are defined
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  - 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
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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)
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    - 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 TMCO 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)
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    - Study period helps define mission, burn down risk

Examples taken from CALIPSO

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  - PI David Winker NASA LaRC
- Three instruments:
  - Dual-wavelength, polarization-sensitive lidar
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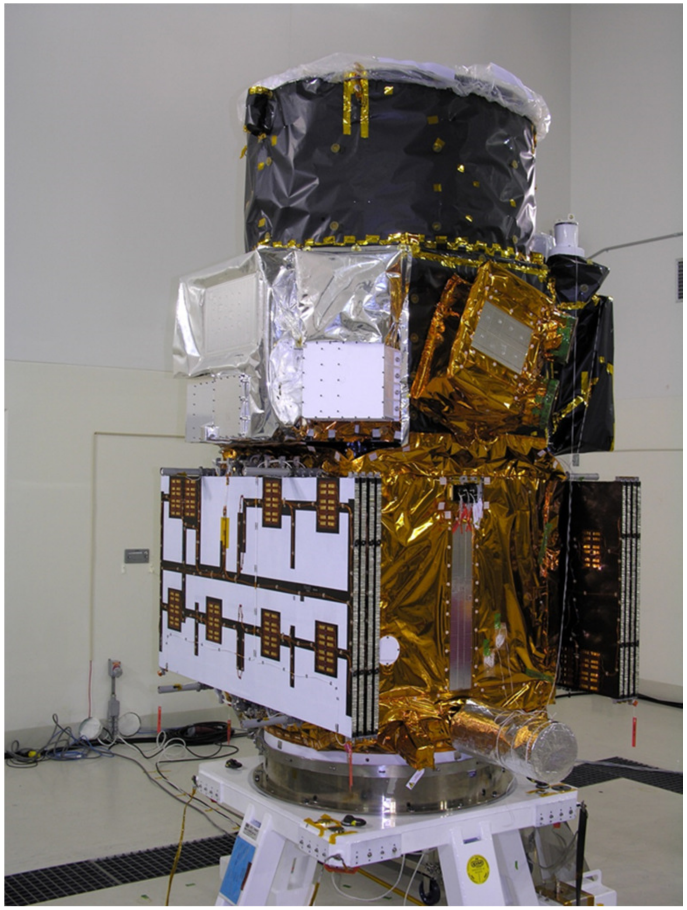

CALIPSO's Path to Space

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  - 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
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  - Examples: LaRC (LITE); GSFC (Shuttle Laser Altimeters)
- Champions developed an international team
- Key new technology for space – Q-switched, Diode-pumped Solid-State Lasers
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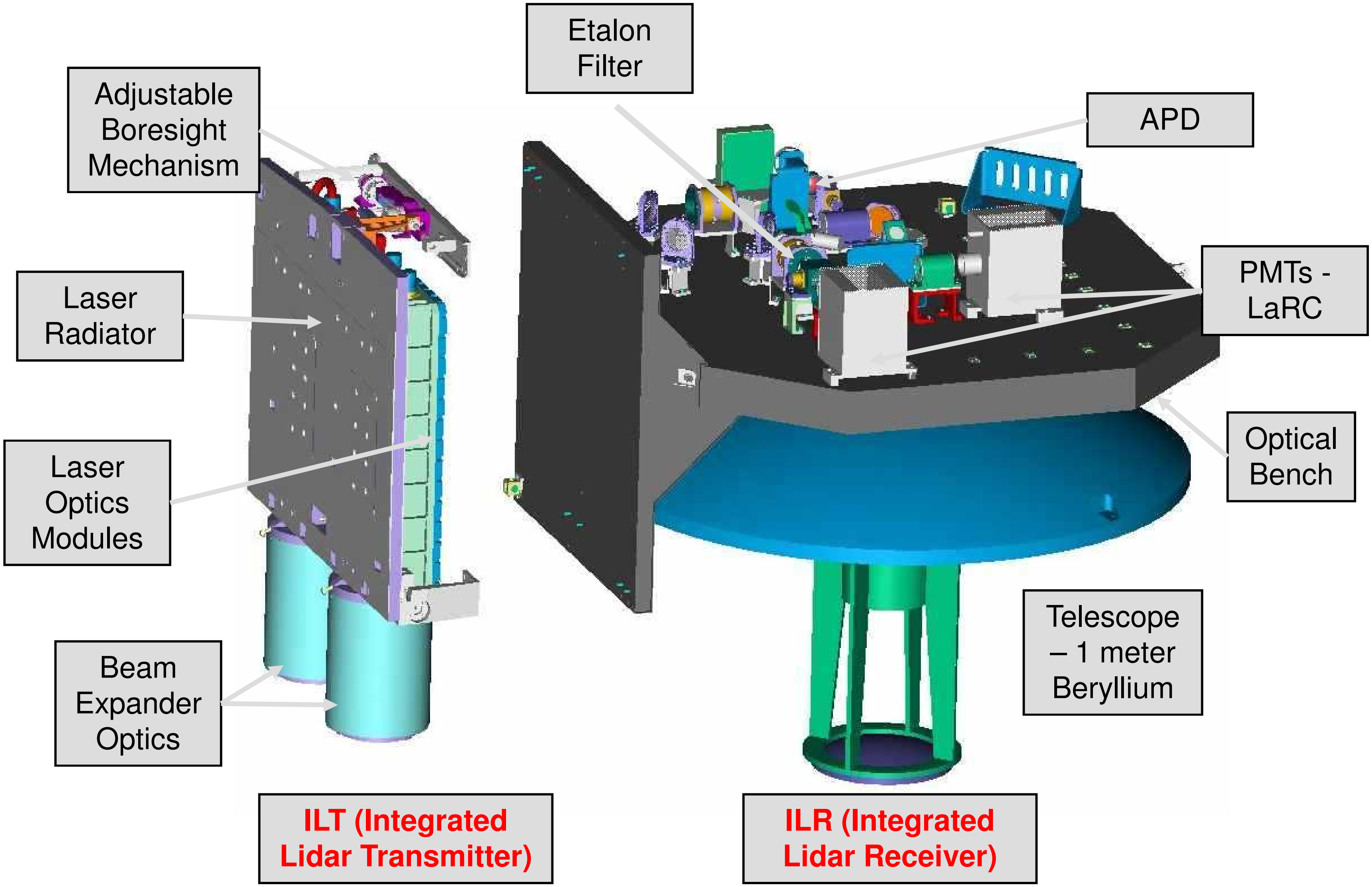
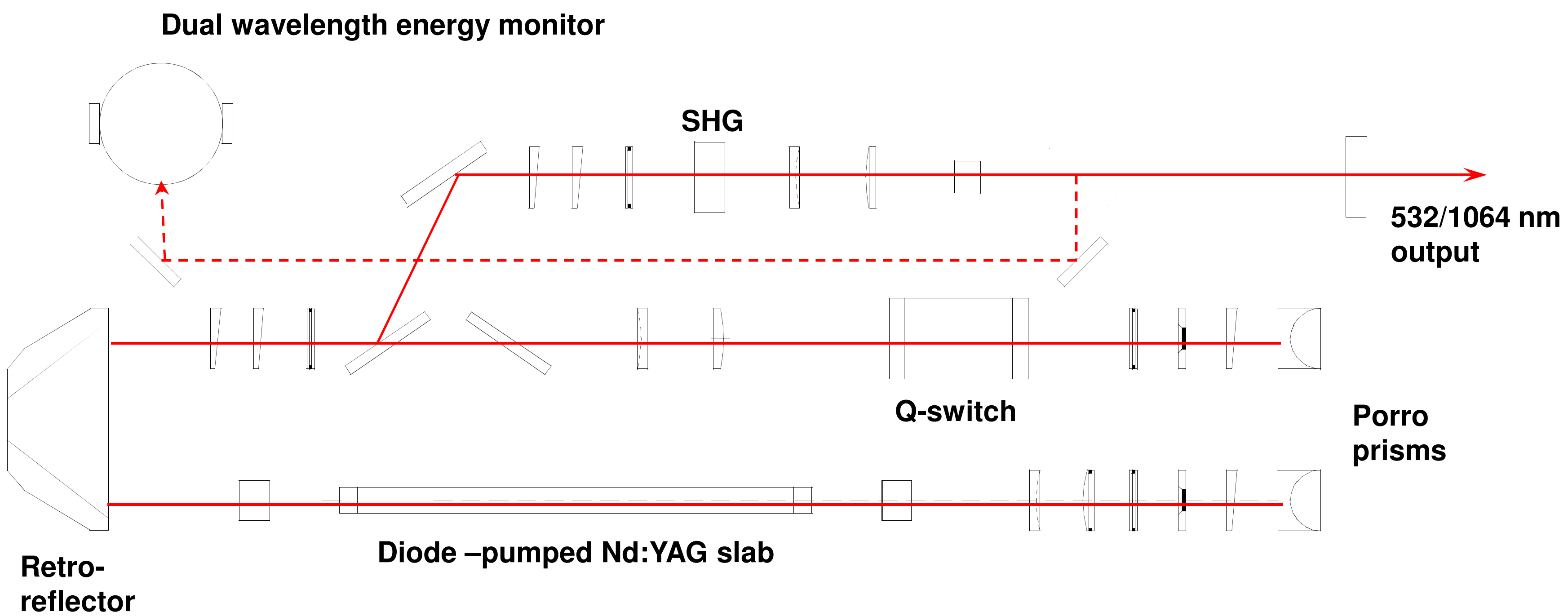
CALIOP Lidar on CALIPSO

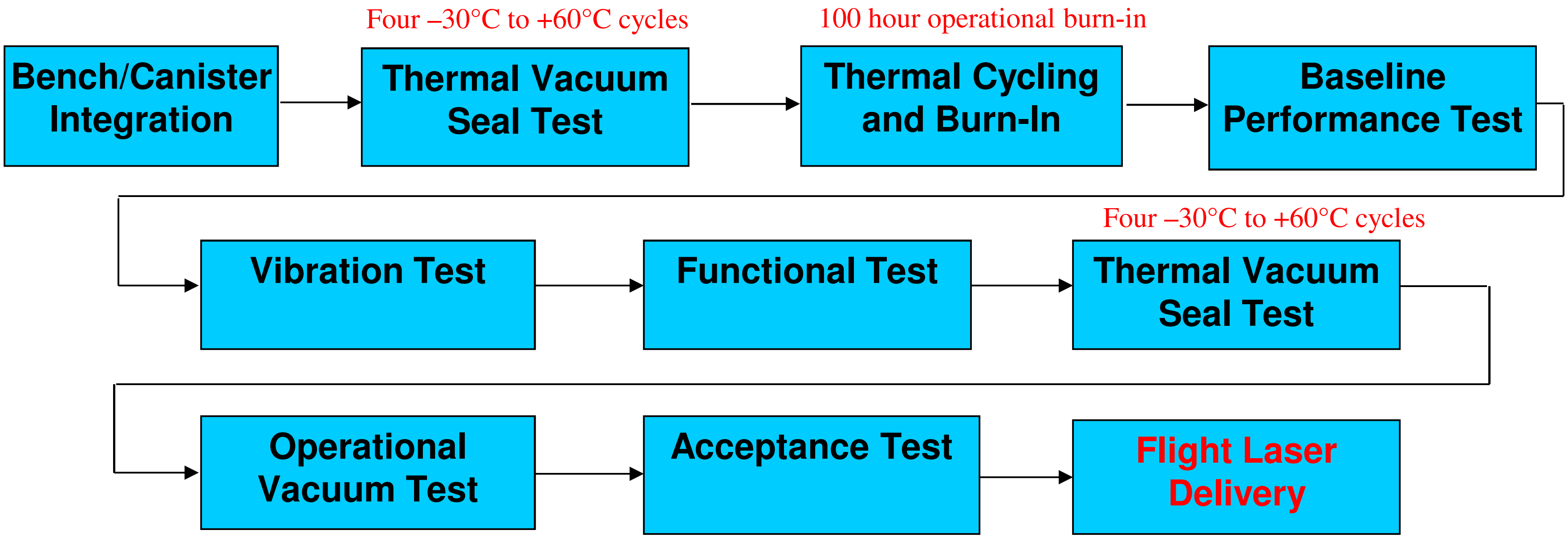


CALIPSO Laser Qualification - Example

- 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				

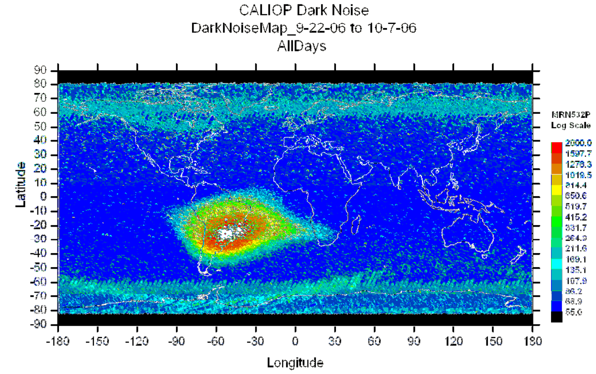
From Coasterpedia: Highest load of a roller coaster 6.3 g – South Africa

Some Lesson Learned from CALIPSO Laser development

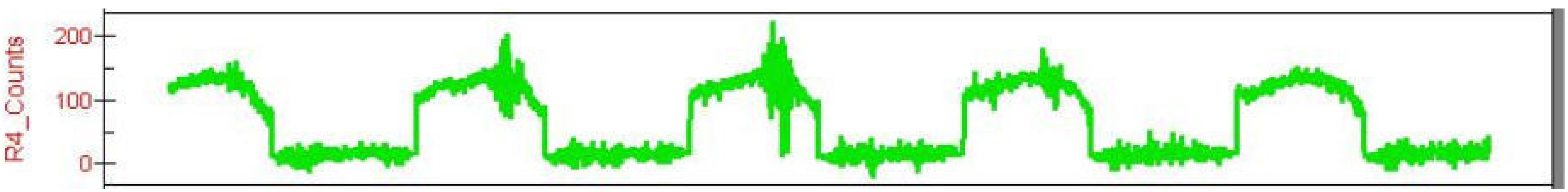
- Use mature laser technologies
  - The cost and schedule constraints of a space-based lidar mission coupled with the logistic complications of any "routine" space mission provide ample opportunities for failure without even introducing a significant technology risk component.
- Use alignment insensitive resonator designs
  - Typical lidar boresight requirements tolerate >100 μrad raw beam wander
  - Many resonators exhibit significant power drop for 100 μrad 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

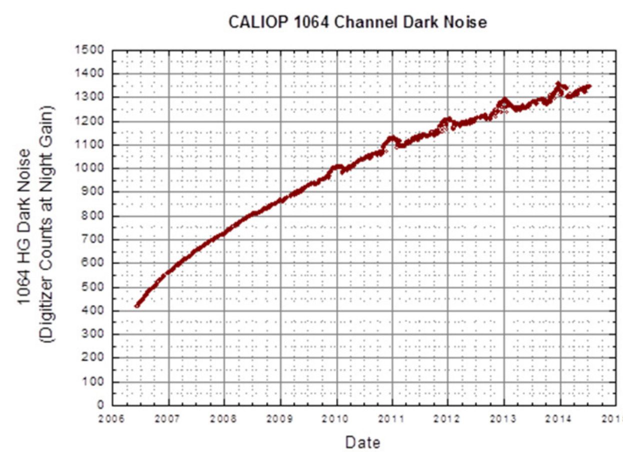
- **CALIPSO uses both Photomultiplier tubes (PMT – 532 nm) and Silicon Avalanche Photodiodes (APD – 1064 nm)**
- **705 km orbit takes the satellite through the South Atlantic Anomaly (SAA) where there is a higher flux of electrons**
- **No damage to PMTs but significant performance loss in SAA**



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

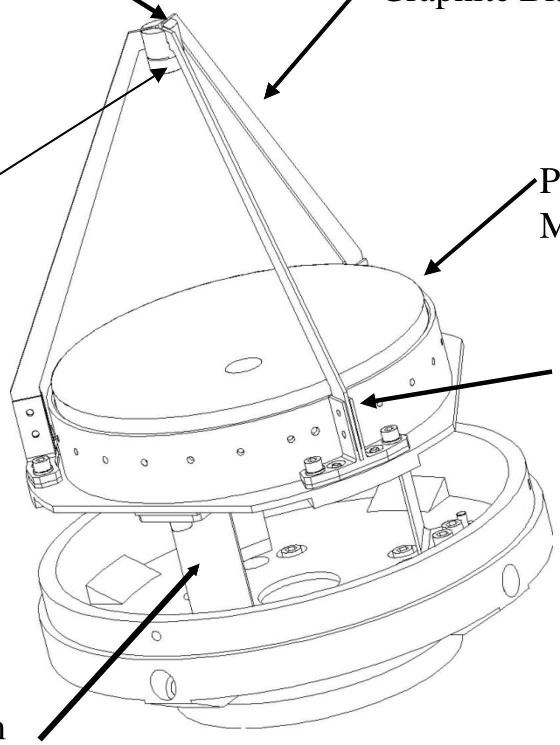


- **The silicon APDs suffer proton displacement damage of the semiconductor leading to a permanent rise in their dark current over time**



Impact of Launch Vibration – Beam Expander Example

- **BEO Lessons Learned**



Total wt: ~5.5 lbs (with sunshade)

Mirrors

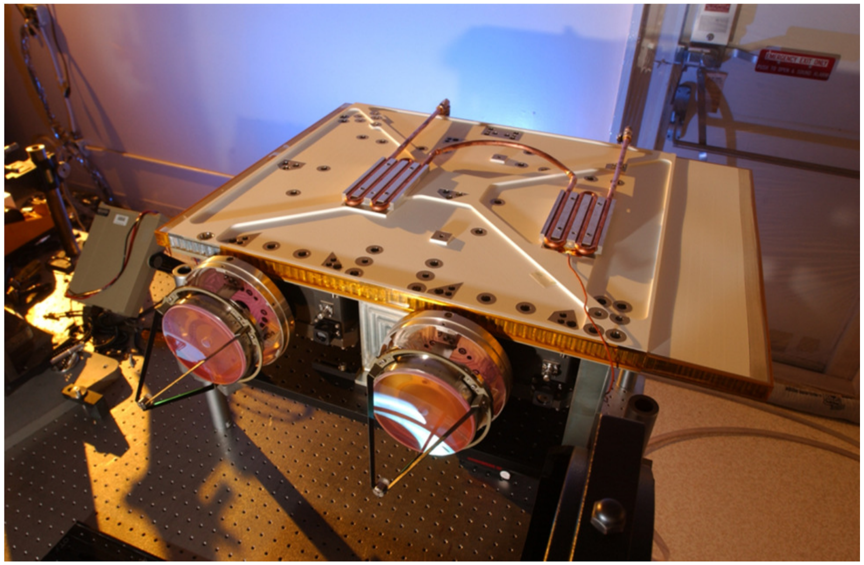
Zerodur substrates

Parabolic (Cassegrain)

λ/20 rms

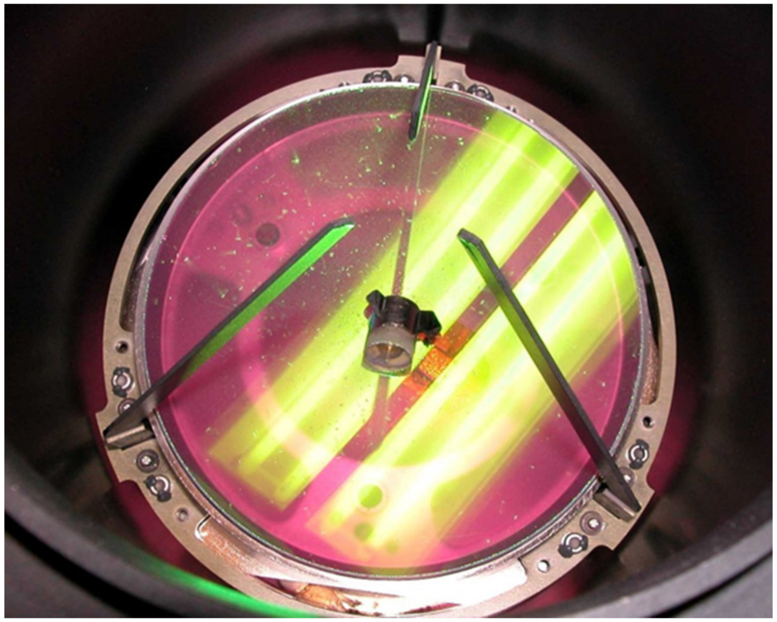
Primary: 125 mm Clear Aperture, f/0.9

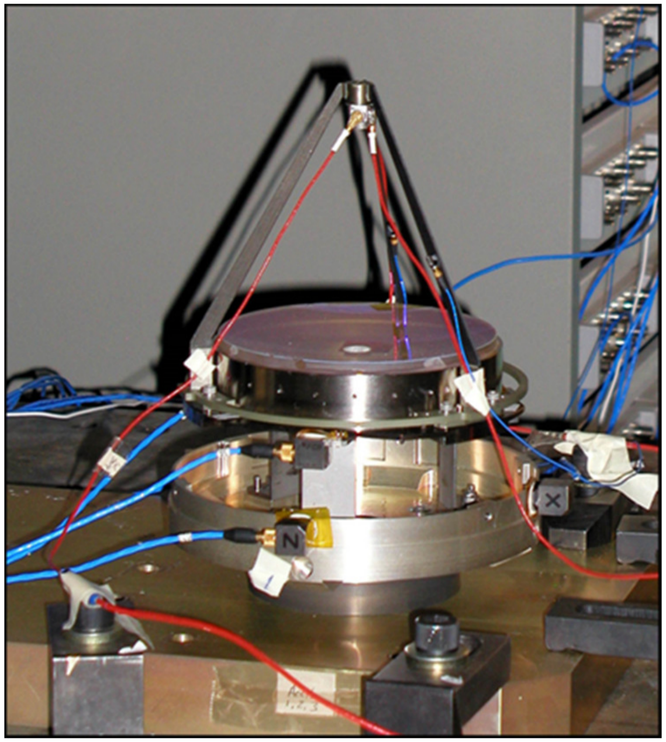
Secondary: 7 mm Clear Aperture, f/0.8



What Vibration Testing can do to precision optics

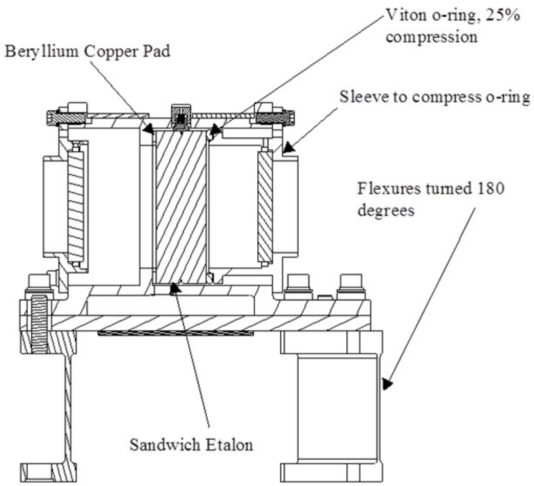
- No Plan (money) to build an Engineering Design Unit, so directly to flight
- Failed in vibration when it reached the full launch levels
- Rebuilt, retested as an EDU – identified five contributing factors to vibration failure
- Redesigned, rebuilt, retested and successful on-orbit



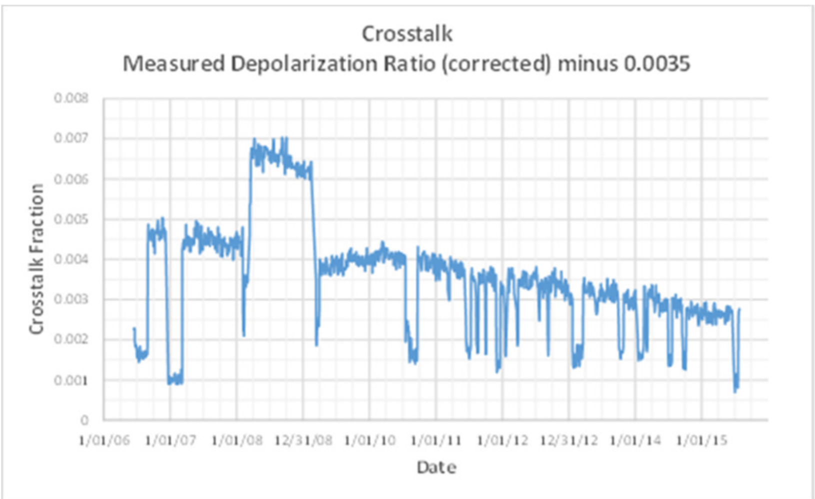


Impact of Thermal - Etalon Example

- 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

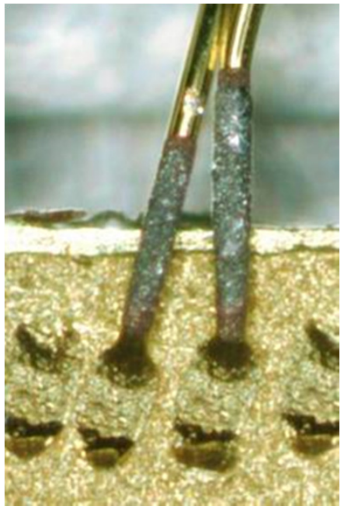


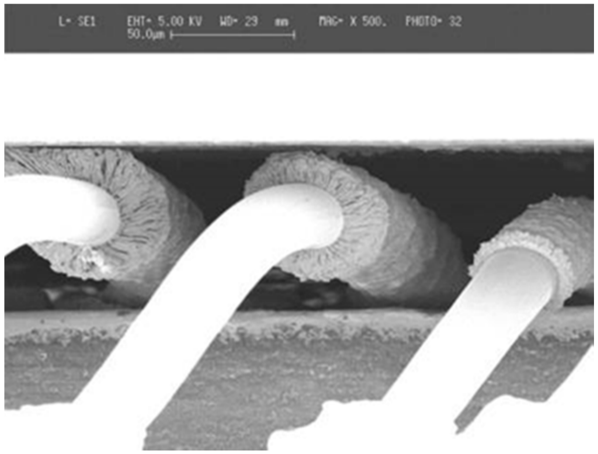
Graphite Bench



Impact of multi-year mission - Materials Example

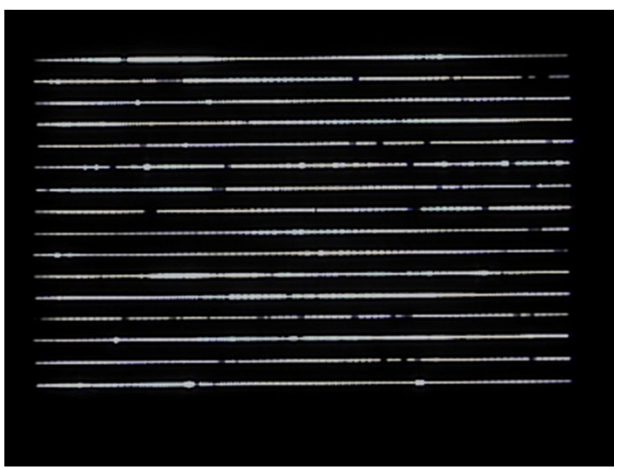
- Gold Indide growth – killed ICEsat's first laser when their diode bars apparently suffered a cascading failure in its diode bars resulting from this effect combined with no derating of the current levels
- Diffusion of indium into gold creates gold indide, a brittle inter-metallic material
- At room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

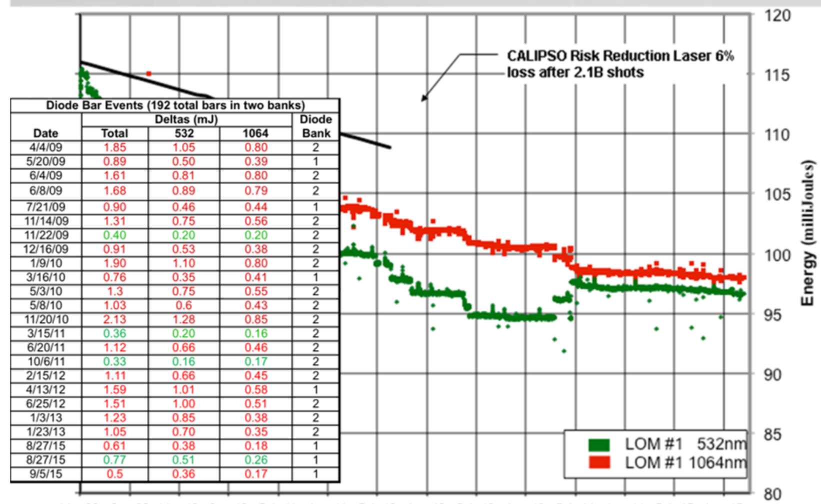




Impact of multi-year mission - Second Materials Example

- 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”





Diode Bar Events (192 total bars in two banks)

Date	Deltas (mJ) Total	532	1064	Diode Bank
4/4/09	1.85	1.05	0.80	2
5/20/09	0.89	0.50	0.39	1
6/4/09	1.61	0.81	0.80	2
6/8/09	1.68	0.89	0.79	2
7/21/09	0.90	0.46	0.44	1
11/14/09	1.31	0.75	0.56	2
11/22/09	0.40	0.20	0.20	2
12/16/09	0.91	0.53	0.38	2
1/9/10	1.90	1.10	0.80	2
3/16/10	0.76	0.35	0.41	1
5/3/10	1.3	0.75	0.55	2
5/8/10	1.03	0.6	0.43	2
11/20/10	2.13	1.28	0.85	2
3/15/11	0.36	0.20	0.16	2
6/20/11	1.12	0.66	0.46	2
10/6/11	0.33	0.16	0.17	2
2/15/12	1.11	0.66	0.45	2
4/13/12	1.59	1.01	0.58	1
6/25/12	1.51	1.00	0.51	2
1/3/13	1.23	0.85	0.38	2
1/23/13	1.05	0.70	0.35	2
8/27/15	0.61	0.38	0.18	1
8/27/15	0.77	0.51	0.26	1
9/5/15	0.5	0.36	0.17	1

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

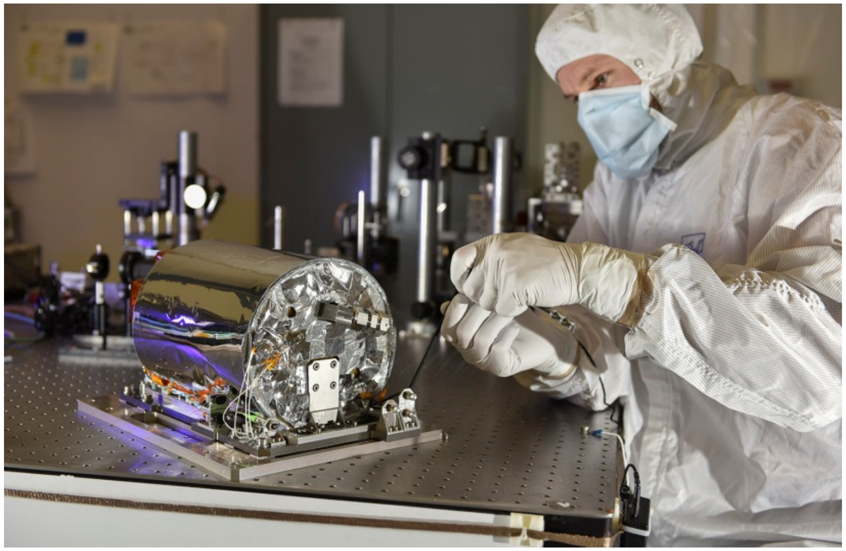
- **Laser frequency combs as a technology have demonstrated amazing scientific results in the lab, it's value to enabling future science from space missions needs to be evaluated against competing approaches**

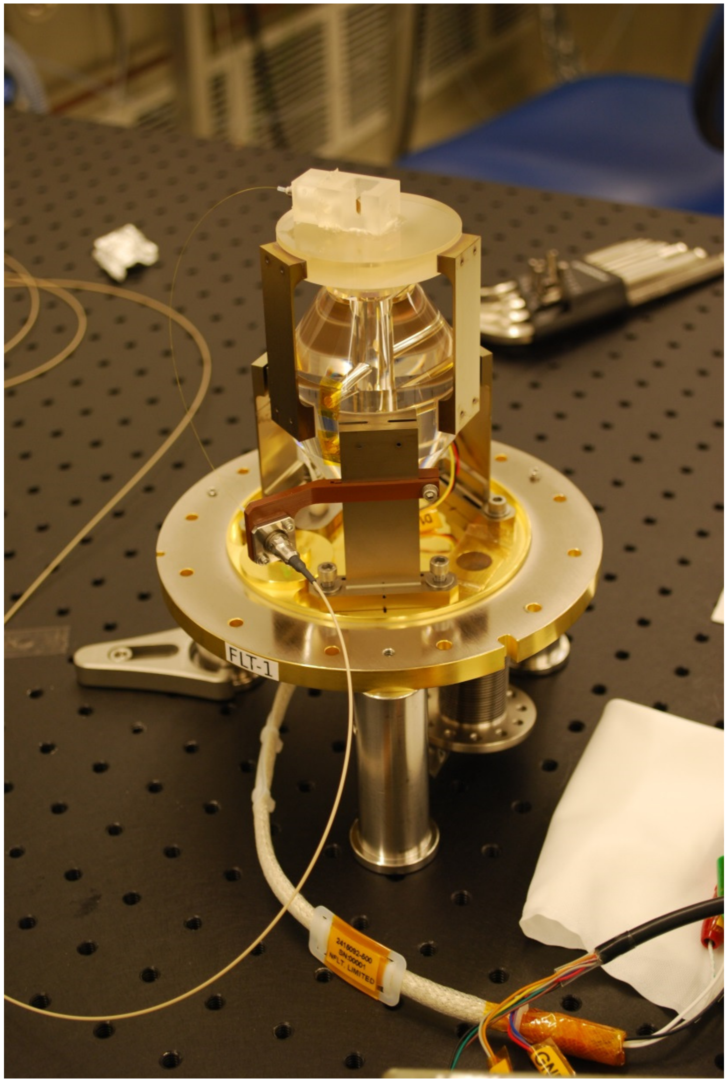
Thanks to the organizers for putting this workshop together and the Keck Foundation for its funding

Back-up

Grace FO Optical Cavity - Example

- Sub-contractor to JPL
- JILA -style optical cavity used to stabilize the lasers to make an interferometric range measurement
- The TRL for space was advanced via a Technology Development program in Earth Science
- Optically Contacted/bonded
- Finesse of 11,500
- Coupling Efficiency 90 %
- Thermal Stability < 7 μK over 100 seconds
- Now in Germany for integration





References

Parts and Radiation:

http://www.nepp.nasa.gov/npsl/npsl_UsePolicy.htm

http://radhome.gsfc.nasa.gov/top.htm

Programmatic:

NPR 7120.5, NASA Space Flight Program and Project Management Handbook

Technologies for Frequency Combs in Space:

Buchs, Kundermann, Portuono-Campa, Lecomte: "Radiation hard mode-locked laser suitable for spaceborne frequency comb" Opt Ex Vol. 23 (2015).

Lee, Lee, Jang, Jang, Han, Lee, Kang, Lim, Kim, Kim: "Testing of a femtosecond pulse laser in outer space" Scientific Reports 4:5134, (2014).

Wilken, Lezius, Hansch, Kohfeldt, Wicht, Schkolnik, Krutzik, Duncker, Hellmig, Windpassinger, Sengstock, Peters, Holzworth: "A frequency comb and precision spectroscopy experiment in space" CLEO (2013).

Girard, Laurent, Pinsard, Robin, Cadier, Boutillier, Marcandella, Boukenter, Ouerdane: "Radiation-hard erbium optical fiber and fiber amplifier for both low- and high-dose space missions" Vol. 39 (2014).

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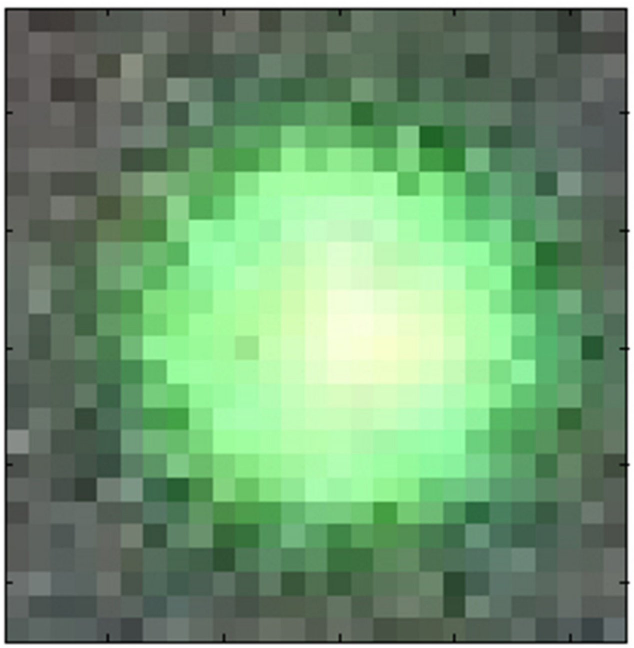

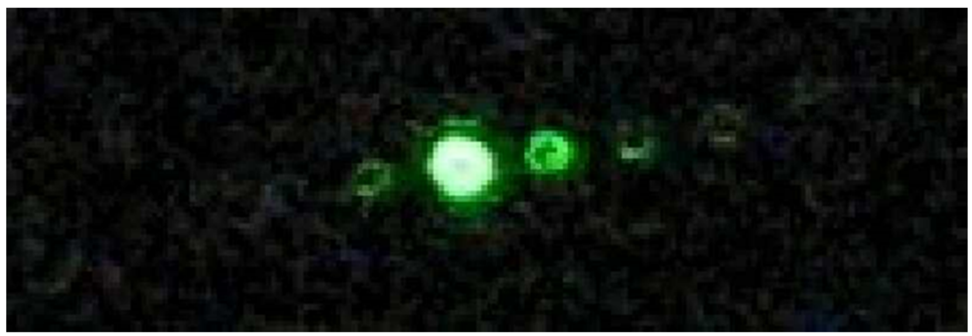

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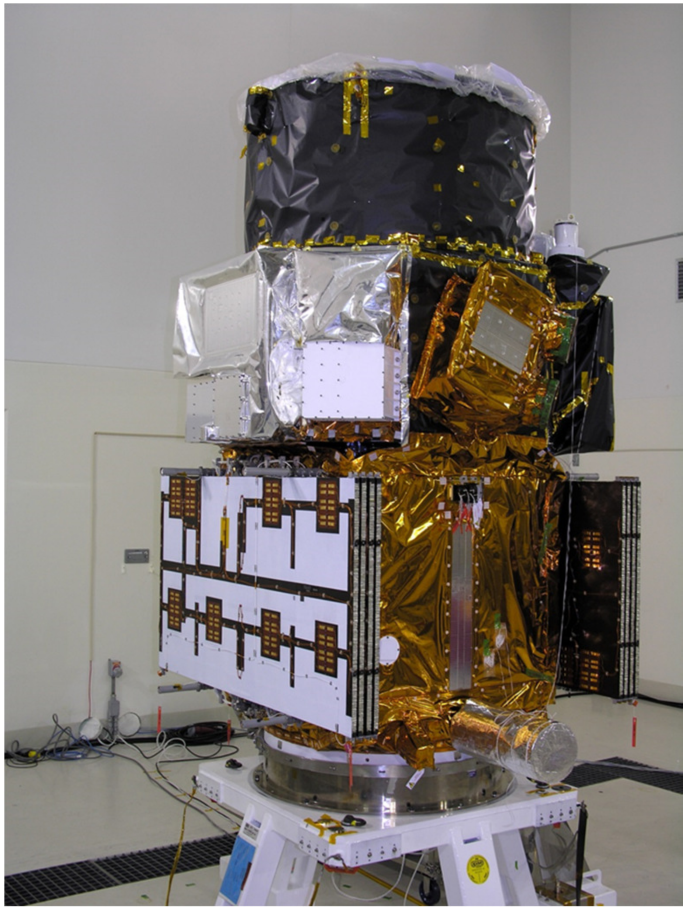

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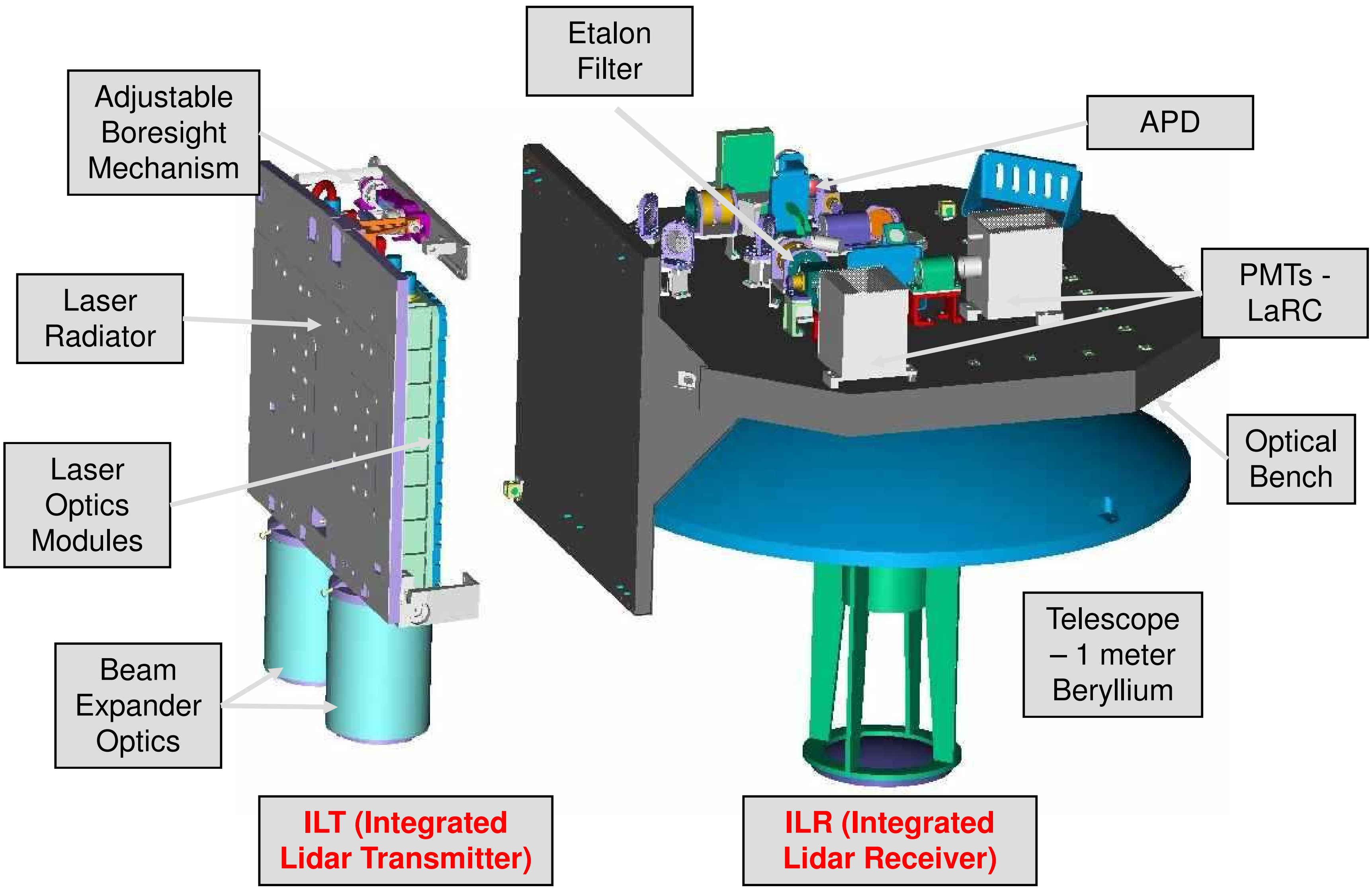

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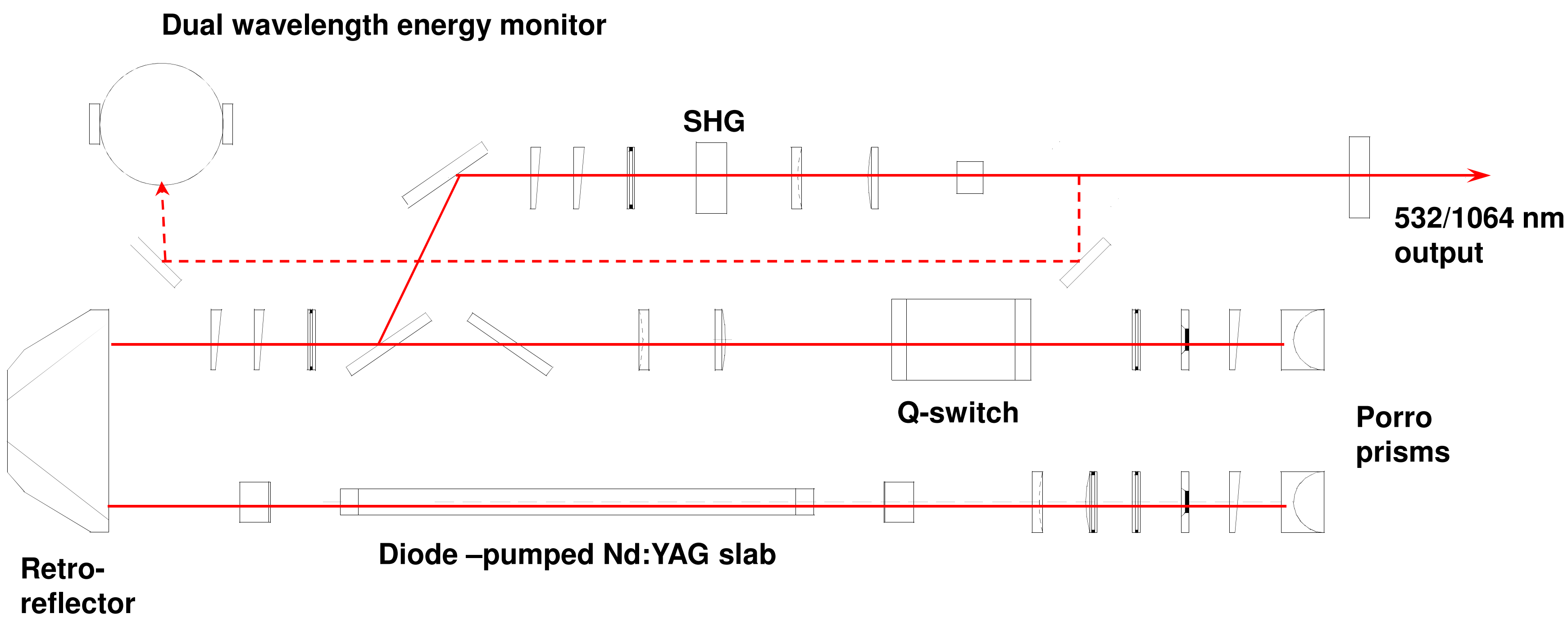
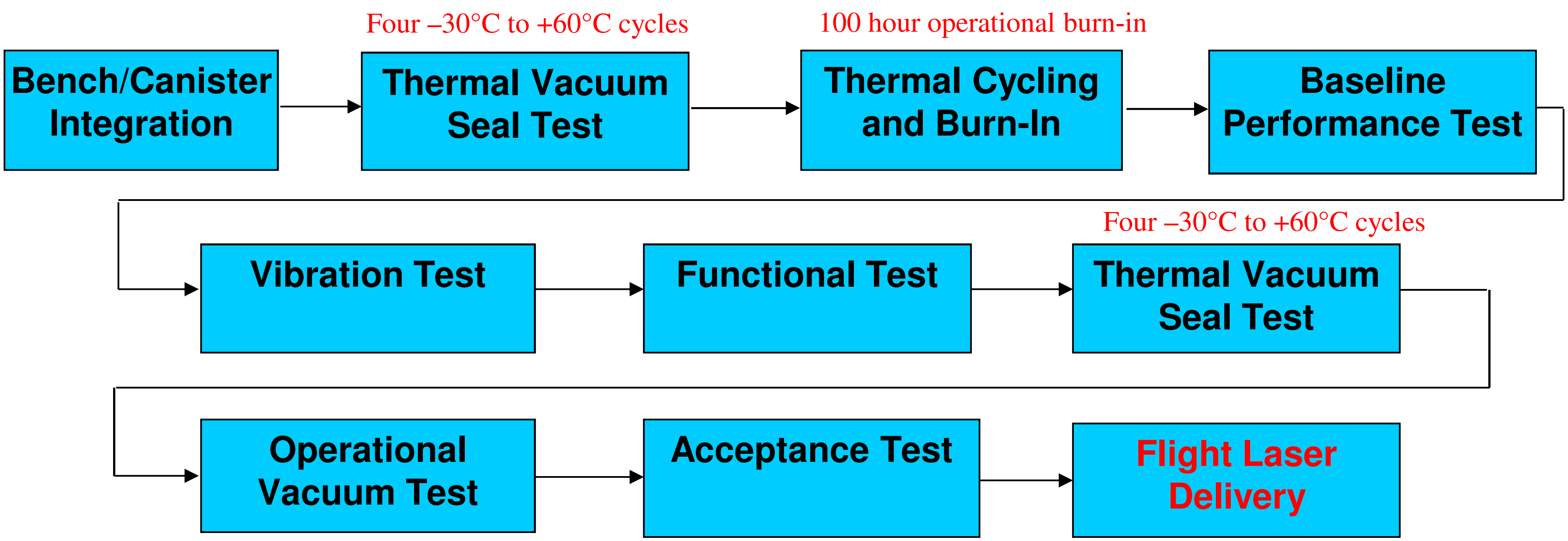


Qualification Test Flow for Flight Laser



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				

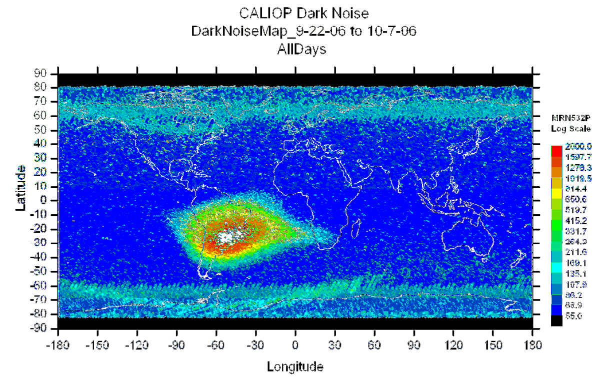
From Coasterpedia: Highest load of a roller coaster 6.3 g – South Africa

Some Lesson Learned from CALIPSO Laser development

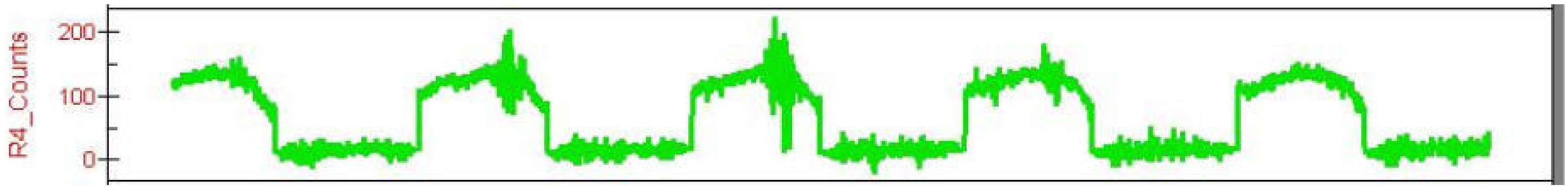
- Use mature laser technologies
  - The cost and schedule constraints of a space-based lidar mission coupled with the logistic complications of any "routine" space mission provide ample opportunities for failure without even introducing a significant technology risk component.
- Use alignment insensitive resonator designs
  - Typical lidar boresight requirements tolerate >100 μrad raw beam wander
  - Many resonators exhibit significant power drop for 100 μrad 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

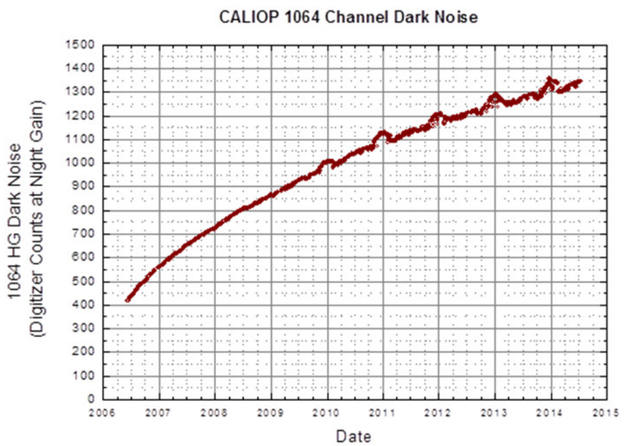
- **CALIPSO uses both Photomultiplier tubes (PMT – 532 nm) and Silicon Avalanche Photodiodes (APD – 1064 nm)**
- **705 km orbit takes the satellite through the South Atlantic Anomaly (SAA) where there is a higher flux of electrons**
- **No damage to PMTs but significant performance loss in SAA**



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

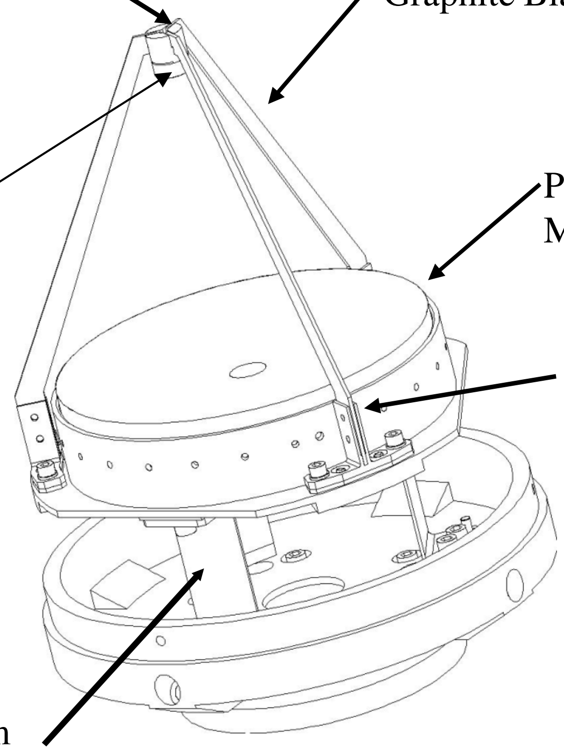


- **The silicon APDs suffer proton displacement damage of the semiconductor leading to a permanent rise in their dark current over time**



Impact of Launch Vibration – Beam Expander Example

- **BEO Lessons Learned**



Total wt: ~5.5 lbs (with sunshade)

Mirrors

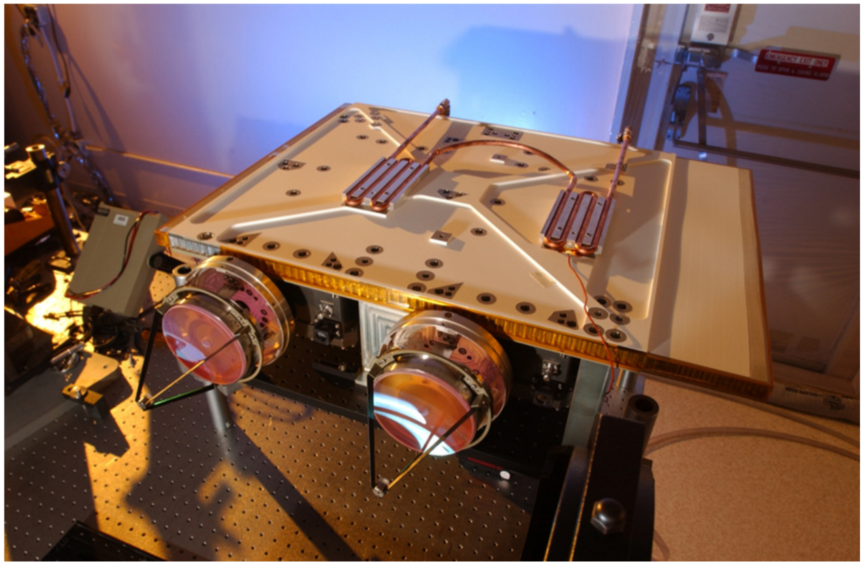
Zerodur substrates

Parabolic (Cassegrain)

λ/20 rms

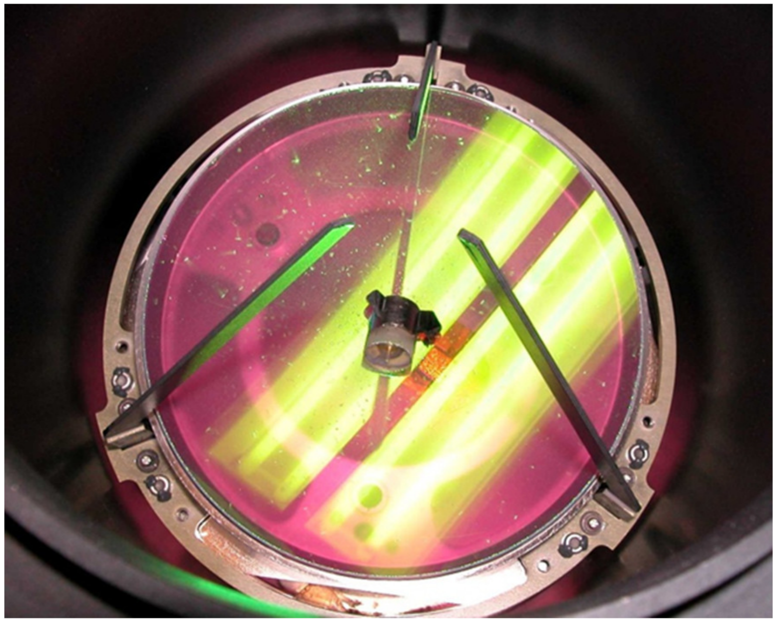
Primary: 125 mm Clear Aperture, f/0.9

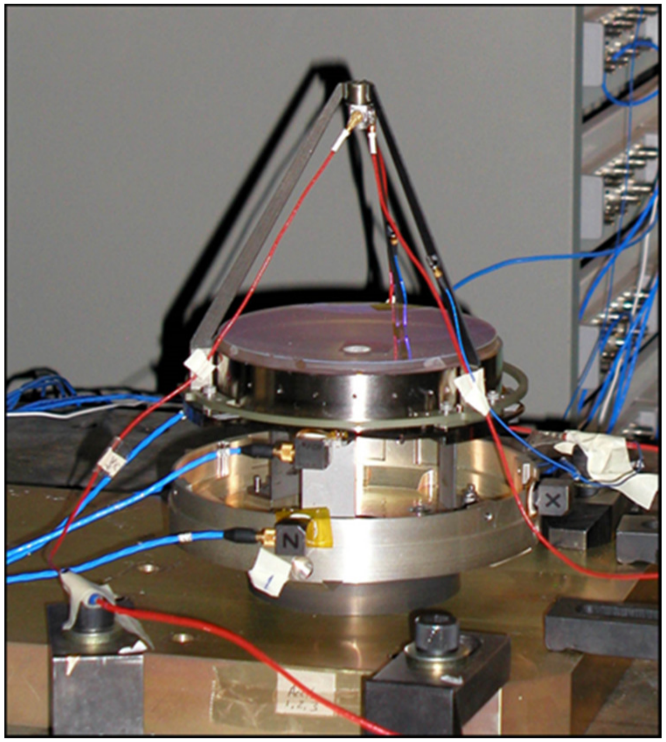
Secondary: 7 mm Clear Aperture, f/0.8



What Vibration Testing can do to precision optics

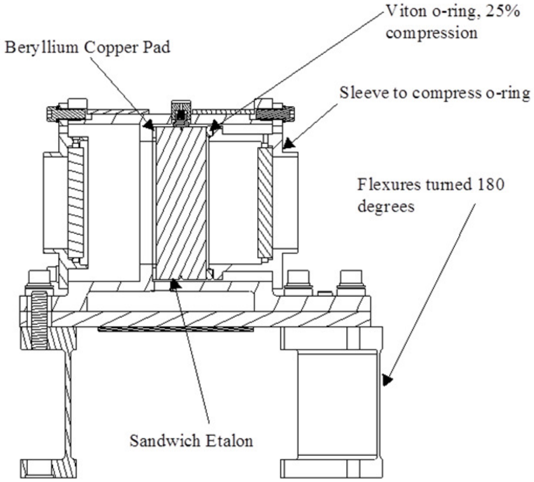
- No Plan (money) to build an Engineering Design Unit, so directly to flight
- Failed in vibration when it reached the full launch levels
- Rebuilt, retested as an EDU – identified five contributing factors to vibration failure
- Redesigned, rebuilt, retested and successful on-orbit



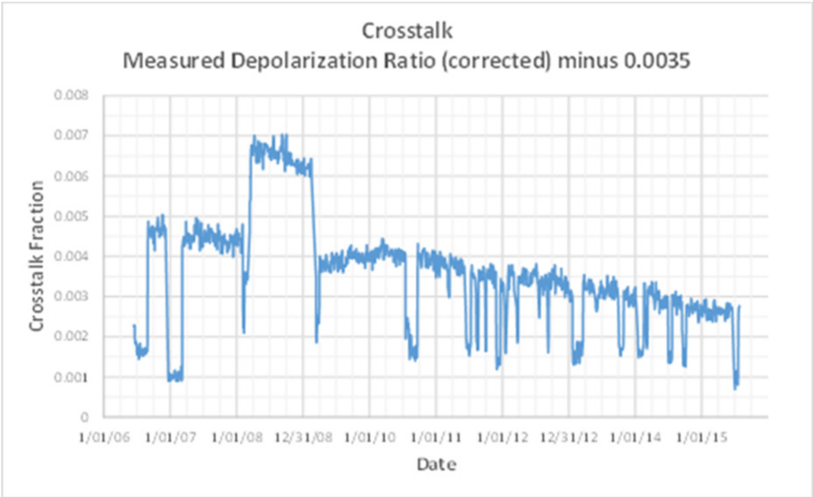


Impact of Thermal - Etalon Example

- 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

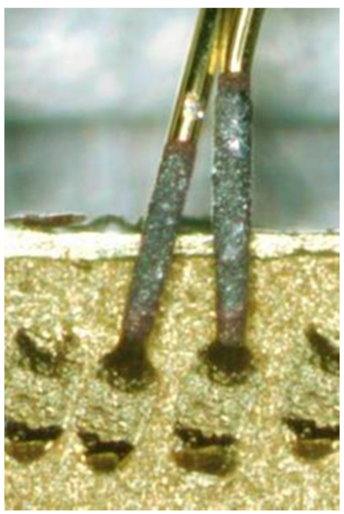


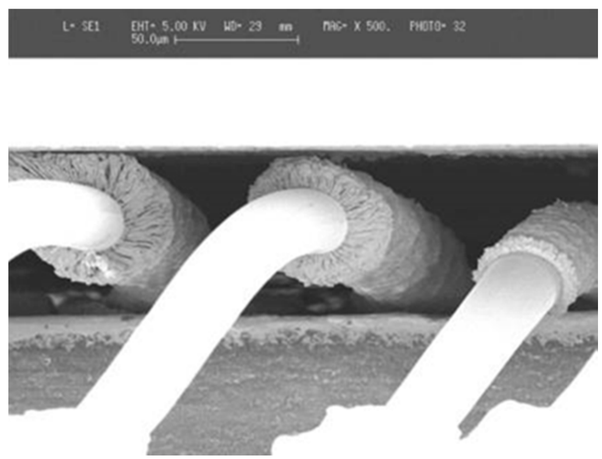
Graphite Bench



Impact of multi-year mission - Materials Example

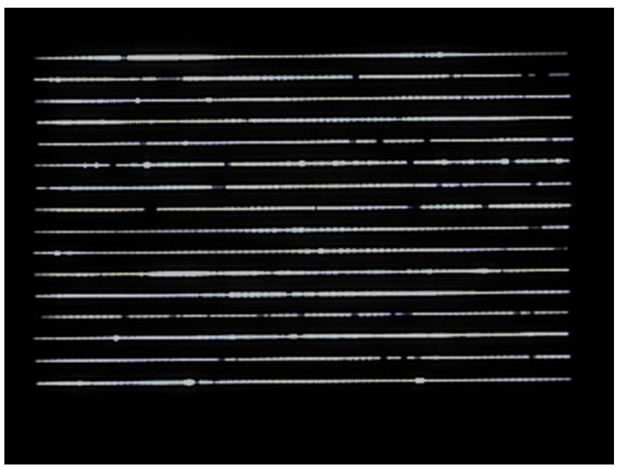
- Gold Indide growth – killed ICEsat’s first laser when their diode bars apparently suffered a cascading failure in its diode bars resulting from this effect combined with no derating of the current levels
- Diffusion of indium into gold creates gold indide, a brittle inter-metallic material
- At room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

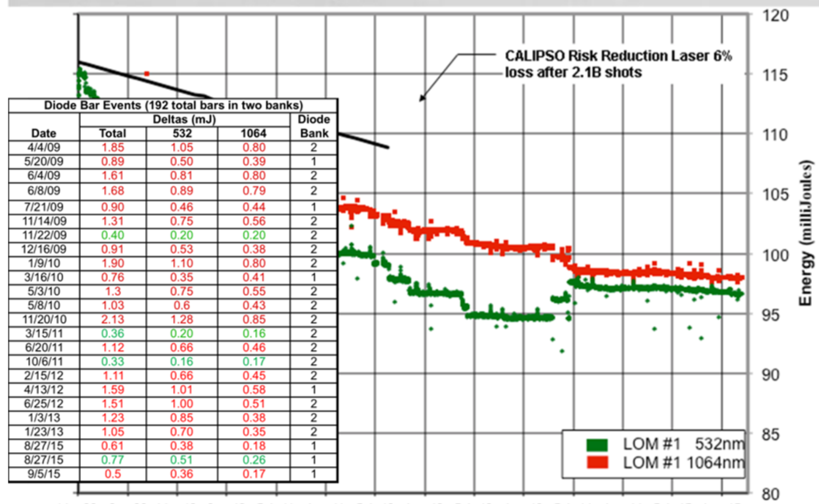




Impact of multi-year mission - Second Materials Example

- 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"





Diode Bar Events (192 total bars in two banks)

Date	Deltas (mJ)			Diode Bank
	Total	532	1064	
4/4/09	1.85	1.05	0.80	2
5/20/09	0.89	0.50	0.39	1
6/4/09	1.61	0.81	0.80	2
6/8/09	1.68	0.89	0.79	2
7/21/09	0.90	0.46	0.44	1
11/14/09	1.31	0.75	0.56	2
11/22/09	0.40	0.20	0.20	2
12/16/09	0.91	0.53	0.38	2
1/9/10	1.90	1.10	0.80	2
3/16/10	0.76	0.35	0.41	1
5/3/10	1.3	0.75	0.55	2
5/8/10	1.03	0.6	0.43	2
11/20/10	2.13	1.28	0.85	2
3/15/11	0.36	0.20	0.16	2
6/20/11	1.12	0.66	0.46	2
10/6/11	0.33	0.16	0.17	2
2/15/12	1.11	0.66	0.45	2
4/13/12	1.59	1.01	0.58	1
6/25/12	1.51	1.00	0.51	2
1/3/13	1.23	0.85	0.38	2
1/23/13	1.05	0.70	0.35	2
8/27/15	0.61	0.38	0.18	1
8/27/15	0.77	0.51	0.26	1
9/5/15	0.5	0.36	0.17	1

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

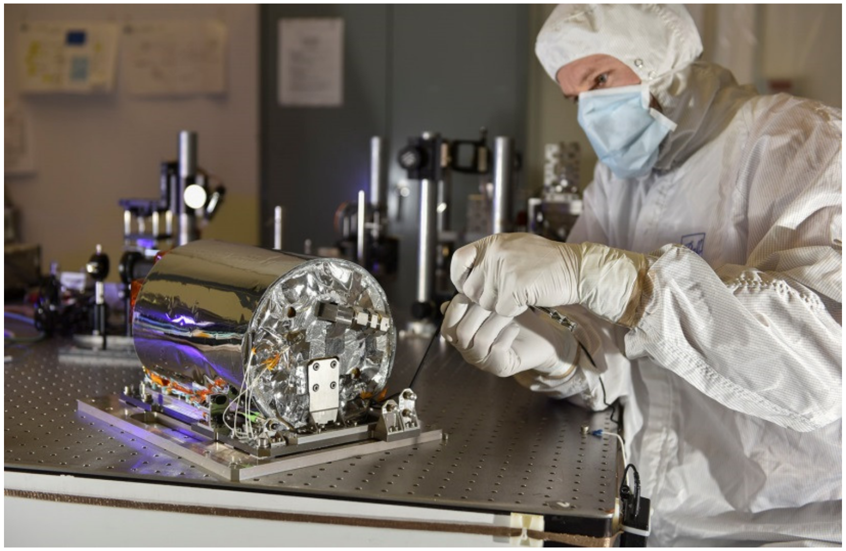
- **Laser frequency combs as a technology have demonstrated amazing scientific results in the lab, it's value to enabling future science from space missions needs to be evaluated against competing approaches**

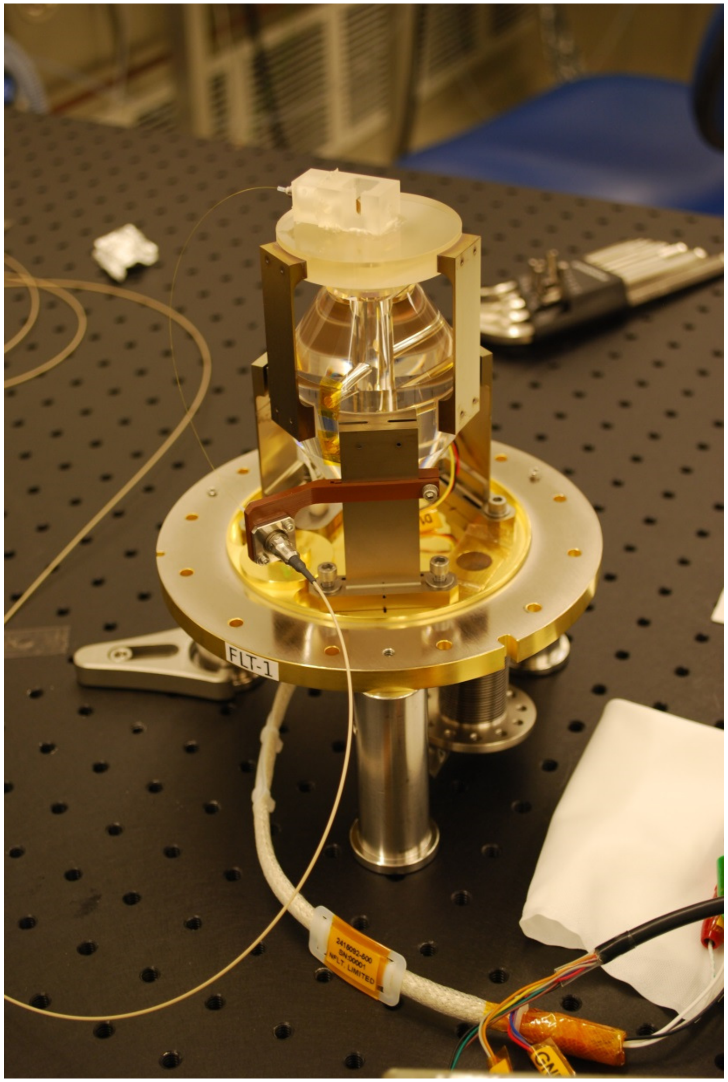
Thanks to the organizers for putting this workshop together and the Keck Foundation for its funding

Back-up

Grace FO Optical Cavity - Example

- Sub-contractor to JPL
- JILA -style optical cavity used to stabilize the lasers to make an interferometric range measurement
- The TRL for space was advanced via a Technology Development program in Earth Science
- Optically Contacted/bonded
- Finesse of 11,500
- Coupling Efficiency 90 %
- Thermal Stability < 7 µK over 100 seconds
- Now in Germany for integration





References

Parts and Radiation:

http://www.nepp.nasa.gov/npsl/npsl_UsePolicy.htm

http://radhome.gsfc.nasa.gov/top.htm

Programmatic:

NPR 7120.5, NASA Space Flight Program and Project Management Handbook

Technologies for Frequency Combs in Space:

Buchs, Kundermann, Portuono-Campa, Lecomte: "Radiation hard mode-locked laser suitable for spaceborne frequency comb" Opt Ex Vol. 23 (2015).

Lee, Lee, Jang, Jang, Han, Lee, Kang, Lim, Kim, Kim: "Testing of a femtosecond pulse laser in outer space" Scientific Reports 4:5134, (2014).

Wilken, Lezius, Hansch, Kohfeldt, Wicht, Schkolnik, Krutzik, Duncker, Hellmig, Windpassinger, Sengstock, Peters, Holzworth: "A frequency comb and precision spectroscopy experiment in space" CLEO (2013).

Girard, Laurent, Pinsard, Robin, Cadier, Boutillier, Marcandella, Boukenter, Ouerdane: "Radiation-hard erbium optical fiber and fiber amplifier for both low- and high-dose space missions" Vol. 39 (2014).