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 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)
    - 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
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

Dual wavelength energy monitor

532/1064 nm output

Retro-reflector

Diode –pumped Nd:YAG slab

Q-switch

Porro prisms

SHG
Qualification Test Flow for Flight Laser

Bench/Canister Integration → Thermal Vacuum Seal Test → Thermal Cycling and Burn-In → Baseline Performance Test

Vibration Test → Functional Test → Thermal Vacuum Seal Test

Operational Vacuum Test → Acceptance Test → Flight Laser Delivery

Four –30°C to +60°C cycles → 100 hour operational burn-in → Four –30°C to +60°C cycles

Response at Radiator Interface

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>ASD (g^2/Hz)</th>
<th>Frequency (Hz)</th>
<th>ASD (g^2/Hz)</th>
<th>Frequency (Hz)</th>
<th>ASD (g^2/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.01</td>
<td>20</td>
<td>0.01</td>
<td>20</td>
<td>0.01</td>
</tr>
<tr>
<td>20-65</td>
<td>4.1 dB/oct</td>
<td>20-55</td>
<td>16.8 dB/oct</td>
<td>20-70</td>
<td>13.0 dB/oct</td>
</tr>
<tr>
<td>65-105</td>
<td>25.0 dB/oct</td>
<td>55-100</td>
<td>-13.9 dB/oct</td>
<td>70-100</td>
<td>-14.2 dB/oct</td>
</tr>
<tr>
<td>105-125</td>
<td>-46.5 dB/oct</td>
<td>100-800</td>
<td>-3.2 dB/oct</td>
<td>100-800</td>
<td>-4.4 dB/oct</td>
</tr>
<tr>
<td>125-450</td>
<td>0.18</td>
<td>800-2000</td>
<td>-2.3 dB/oct</td>
<td>800-2000</td>
<td>-2.3 dB/oct</td>
</tr>
<tr>
<td>450-800</td>
<td>-11.5 dB/oct</td>
<td>Overall Grms:</td>
<td>10.67</td>
<td>Overall Grms:</td>
<td>11.58</td>
</tr>
<tr>
<td>800-2000</td>
<td>-2.3 dB/oct</td>
<td>Overall Grms:</td>
<td>12.12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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
- 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

  - Graphite Blades
  - Titanium Flexure
  - Invar Mount
  - Secondary Mirror

Mirrors

  - Zerodur substrates
  - Parabolic (Cassegrain)
  - λ/20 rms
  - Primary: 125 mm Clear Aperture, f/0.9
  - Secondary: 7 mm Clear Aperture, f/0.8

Total wt: ~5.5 lbs (with sunshade)
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. -30°C to + 60°C) 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
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
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:
From the Lab to Space: Comments on Instrument Qualification

Dr. Carl Weimer
Ball Aerospace & Technologies Corporation
11/2/15 – KISS
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
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 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)
  - 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 a 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

- Adjustable Boresight Mechanism
- Laser Radiator
- Laser Optics Modules
- Beam Expander Optics
- Etalon Filter
- APD
- PMTs - LaRC
- Optical Bench
- Telescope – 1 meter Beryllium

ILT (Integrated Lidar Transmitter)
ILR (Integrated Lidar Receiver)
- 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

Dual wavelength energy monitor

532/1064 nm output
Qualification Test Flow for Flight Laser

**Bench/Canister Integration** → **Thermal Vacuum Seal Test** → **Thermal Cycling and Burn-In** → **Baseline Performance Test**

- **Four –30°C to +60°C cycles**

**Vibration Test** → **Functional Test** → **Thermal Vacuum Seal Test**

- **Four –30°C to +60°C cycles**

**Operational Vacuum Test** → **Acceptance Test** → **Flight Laser Delivery**

**Response at Radiator Interface**

<table>
<thead>
<tr>
<th></th>
<th>X Axis</th>
<th></th>
<th>Y Axis</th>
<th></th>
<th>Z Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. (Hz)</td>
<td>ASD (g^2/Hz)</td>
<td>Freq. (Hz)</td>
<td>ASD (g^2/Hz)</td>
<td>Freq. (Hz)</td>
</tr>
<tr>
<td>20</td>
<td>0.01</td>
<td>0.01</td>
<td>20</td>
<td>0.01</td>
<td>20</td>
</tr>
<tr>
<td>20-65</td>
<td>4.1 dB/oct</td>
<td>20-55</td>
<td>16.8 dB/oct</td>
<td>20-70</td>
<td>13.0 dB/oct</td>
</tr>
<tr>
<td>65-105</td>
<td>25.0 dB/oct</td>
<td>55-100</td>
<td>-13.9 dB/oct</td>
<td>70-100</td>
<td>-14.2 dB/oct</td>
</tr>
<tr>
<td>105-125</td>
<td>-46.5 dB/oct</td>
<td>100-800</td>
<td>-3.2 dB/oct</td>
<td>100-800</td>
<td>-4.4 dB/oct</td>
</tr>
<tr>
<td>125-450</td>
<td>0.18</td>
<td>800-2000</td>
<td>-2.3 dB/oct</td>
<td>800-2000</td>
<td>-2.3 dB/oct</td>
</tr>
<tr>
<td>450-800</td>
<td>-11.5 dB/oct</td>
<td>Overall Grms: 10.67</td>
<td>Overall Grms: 11.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>800-2000</td>
<td>-2.3 dB/oct</td>
<td>Overall Grms: 12.12</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

**Overall Grms:** 12.12
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 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**
  - Invar mount
  - Graphite Blades
  - Secondary Mirror
  - Primary Mirror
  - Invar foot
  - Titanium Flexure

**Mirrors**
- Zerodur substrates
- Parabolic (Cassegrain)
- \( \lambda/20 \) rms
- Primary: 125 mm Clear Aperture, f/0.9
- Secondary: 7 mm Clear Aperture, f/0.8

Total wt: ~5.5 lbs (with sunshade)
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. -30°C to +60°C) 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
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.
- 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
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/npnlsUsePolicy.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: