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Design, Qualification, and On Orbit Performance of the CALIPSO Aerosol Lidar Transmitter

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Presentation Overview

- **Requirements**
- **Design overview**
- **Approach to qualification**
- **On-orbit laser transmitter performance**

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Performance Requirements

Laser performance requirements are not particularly stressing from a laser design viewpoint

• 1064 nm energy	100-125 mJ
• 532 nm energy	100-125 mJ
• Pulse width	15 ns < Δt < 50 ns
• Repetition rate	20 Hz
• Beam quality	< 10 mm-mrad, both λ
• 1064 nm line width	< 150 pm
• 532 nm line width	< 35 pm
• 532 nm polarization	> 100:1 linear
• Beam co-linearity	< 10 % of output divergence
• Beam jitter	< 10 % of output divergence

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Performance Requirements

System level requirements are more challenging

- Lifetime of 2 billion shots
- Pure conduction cooling
- Fully redundant lasers and electronics
- Modest thermal requirements
  - Operate within specification in a +/- 5°C band around optimum (~20°C)
  - Operate without damage from -5°C to 30°C
  - No impact from non-operational -30°C to +60°C thermal cycling
- Power requirements are somewhat challenging
  - No more than 20 W required in standby
  - No more than 102 W required operationally
- Severe vibrational requirements (>10.5 g_{rms})
- Dual wavelength energy monitors with +/-2% precision over full orbit
  - Based on integrating sphere technology
- 100 µrad +/- 10 µrad final divergence required matched shimming of Beam Expander Optics to each laser
- Electro-Magnetic Interference specification

Optical Design Overview

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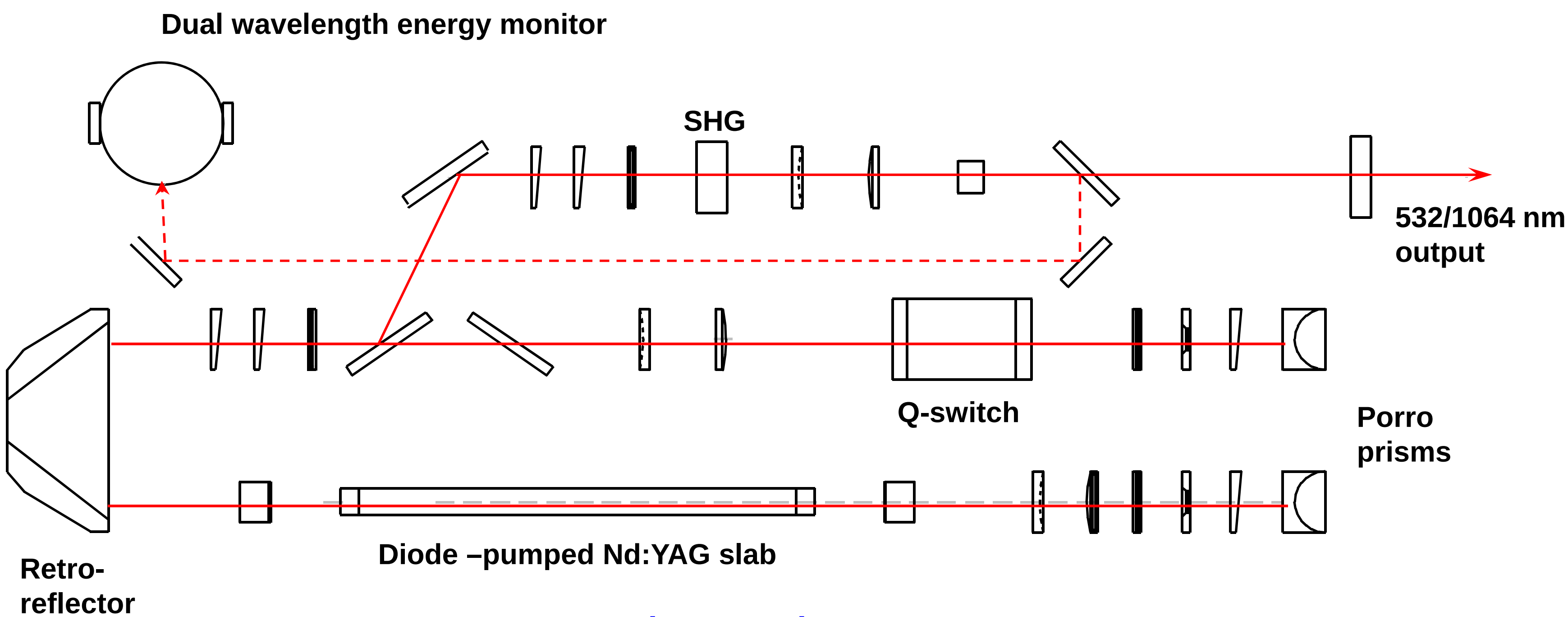
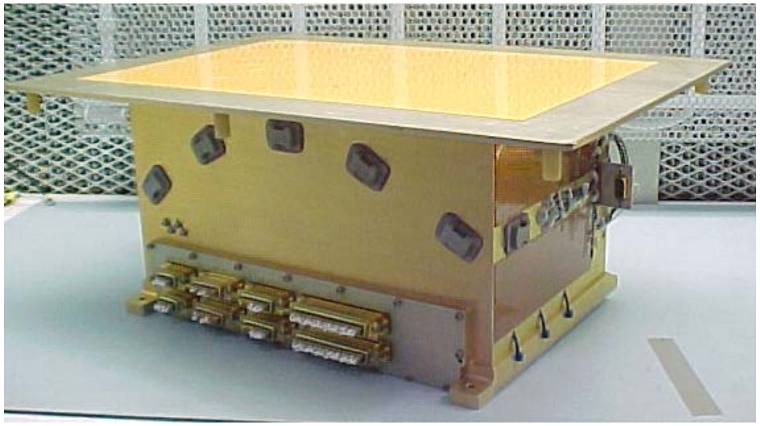
- Crossed porro prism resonator for alignment insensitivity
- Dual wavelength energy monitor with < +/-1% precision
- Second harmonic generation with KTP
- Diode pumped Nd:YAG slab gain medium
- Conductively cooled



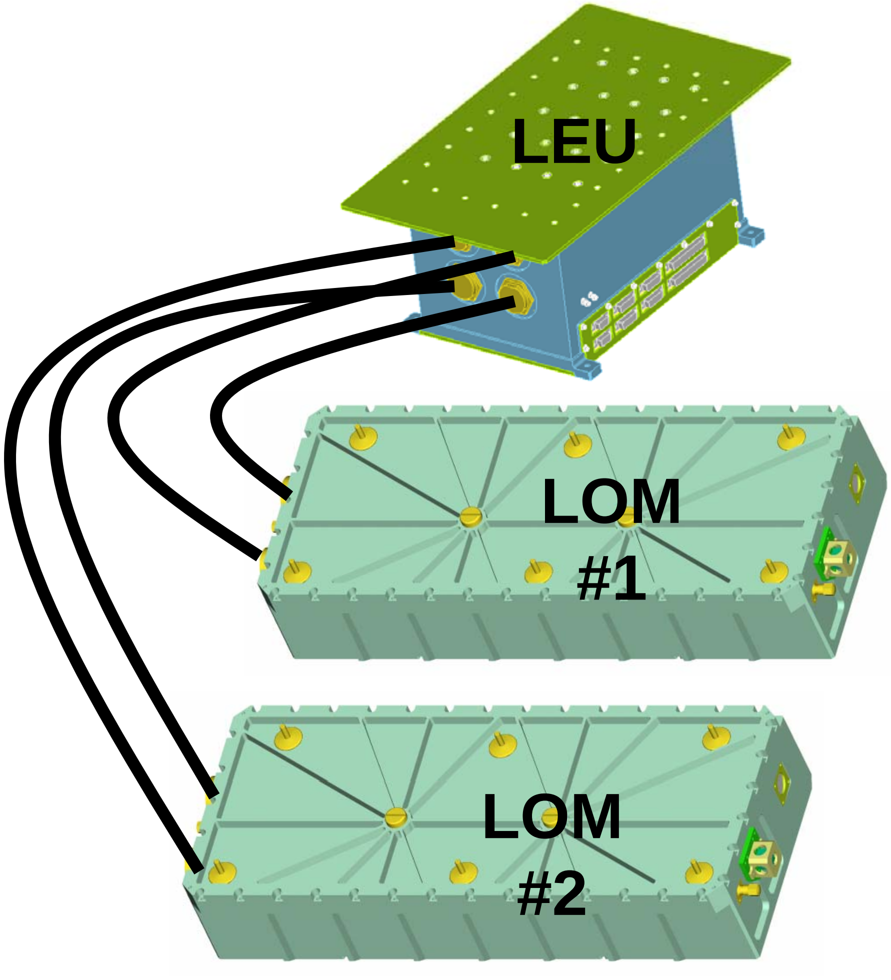
Crossed porro prism resonator

Laser System Overview

- **Fully redundant lasers and electronics**
- **Sealed laser canisters**
  - **Operation in air is is better characterized from extensive lifetime testing**
  - **Reduced sensitivity to trace contamination**
- **High efficiency electronics**
  - **Dynamic diode voltage control**



Laser Electronics Unit



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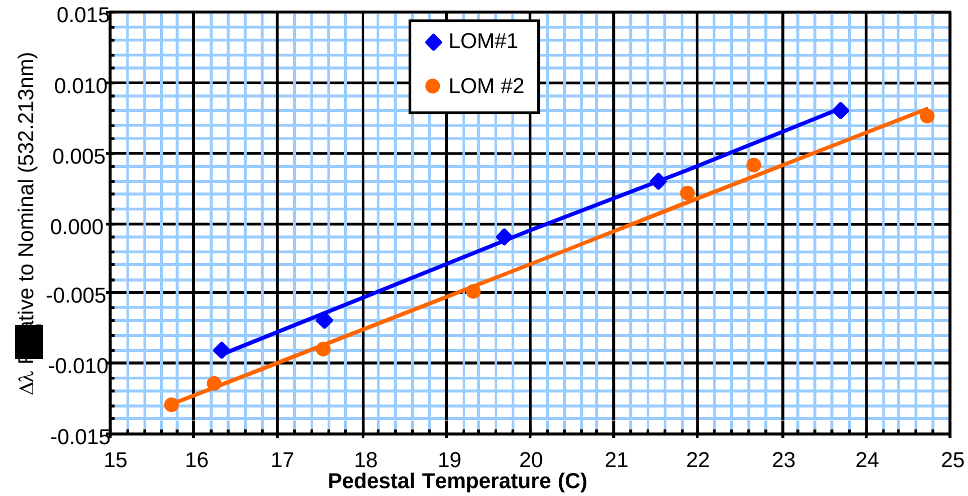
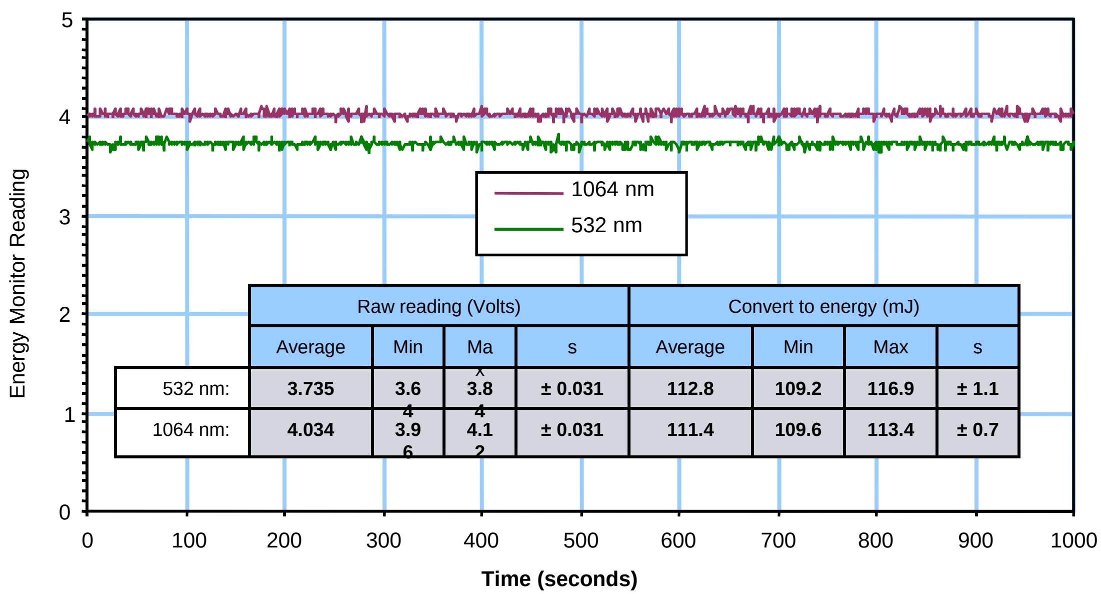
Pre-Launch Laser Stability

- Energy monitor precision over full orbit ≤ 2%
- Shot-to-shot energy jitter is ≤ 1.1%
- 532 nm wavelength varies ~ 20 pm over a 10°C change
  - Value is consistent with the temperature shift of the Nd:YAG emission profile
- Laser output energy unchanged since delivery in 2002
- > 99.5% of the of the pulses had pointing jitter that was <10% of the full beam divergence



532 nm wavelength vs. laser head temperature

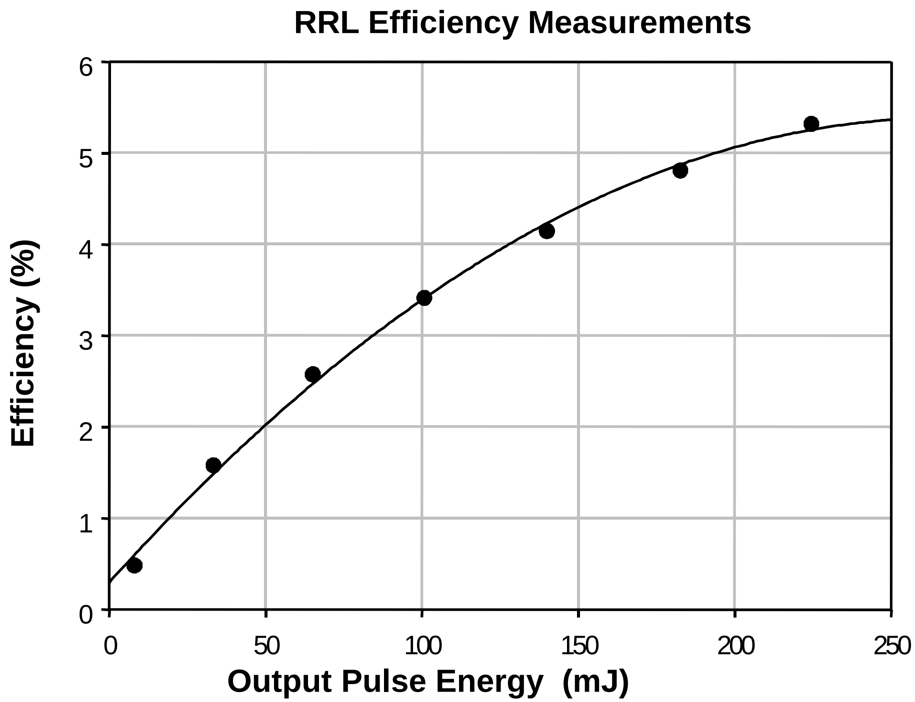


	Raw reading (Volts)				Convert to energy (mJ)			
	Average	Min	Max	s	Average	Min	Max	s
532 nm:	3.735	3.64	3.84	± 0.031	112.8	109.2	116.9	± 1.1
1064 nm:	4.034	3.96	4.12	± 0.031	111.4	109.6	113.4	± 0.7

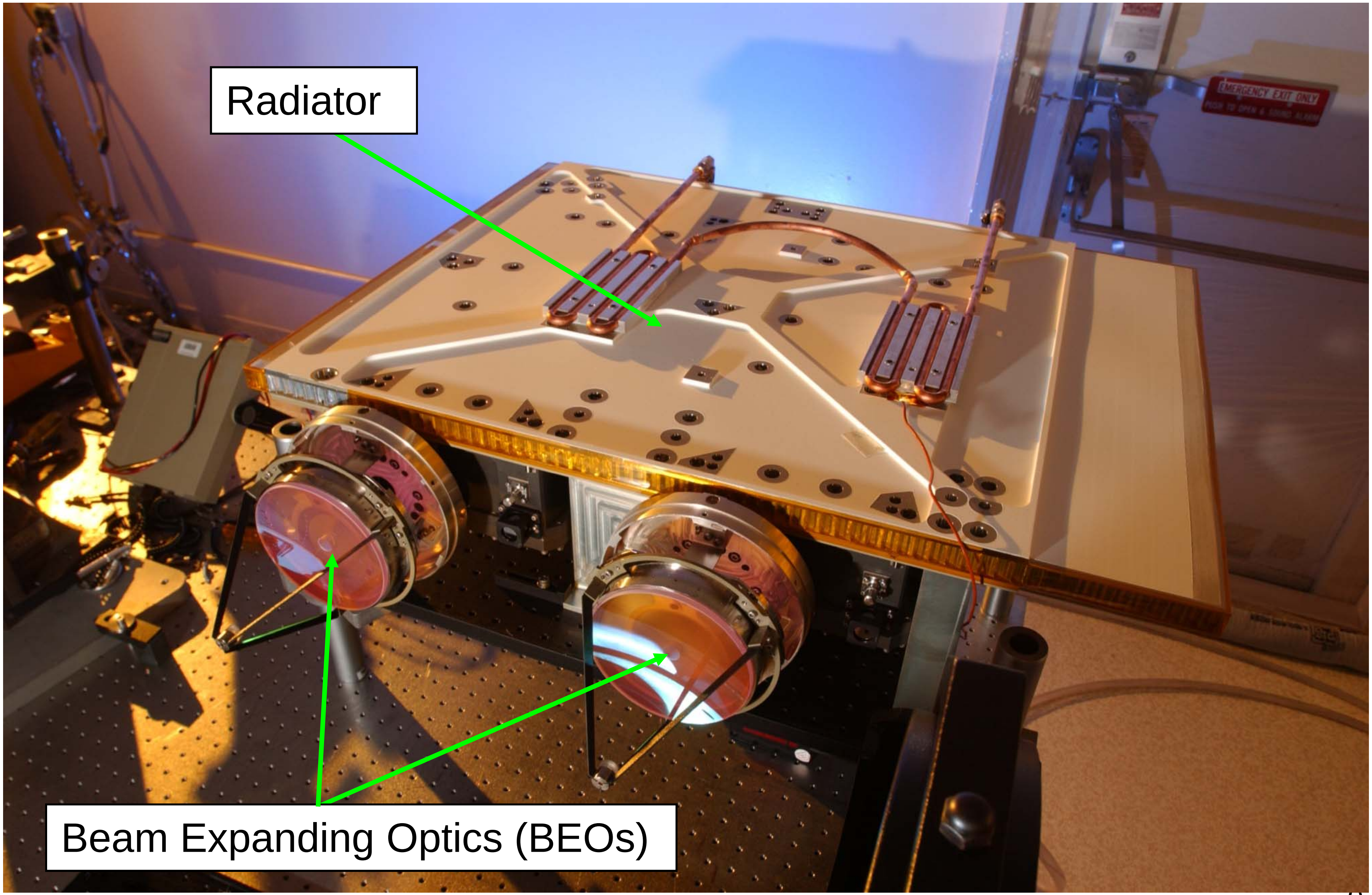
Shot-to-shot energies

Laser Efficiency

- RRL measurements with the RRL show that higher efficiencies are achieved with higher pulse energies
- Two key efficiency drivers: 1) electrical power conversion efficiency & 2) spectral overlap of diodes with Nd:YAG absorption bands
  - Electrical power conversion efficiency of 83%
  - Spectral overlap somewhat off peak due to requirement to match peak 532 nm etalon transmission
- LOM 1 wall plug efficiency was 4.2% (4.4 W output for 104 W total electrical input)
- LOM 2 wall plug efficiency was 4.4% (4.4 W output for 100 W total electrical input)



Integrated Laser Transmitter



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Laser Environmental Qualification

A systematic approach to laser qualification, beginning at the optical subassembly level and proceeding incrementally to the full module level, resulted in the successful qualification of both Laser Optic Modules as well as the Laser Electronics Unit

Optical component and subassembly testing

- Nd:YAG slab
- Corner cube
- Steering prism
- Telescope
- Porro prism
- Q-switch
- Second harmonic generator
- Diode arrays

→

Module vibration and seal testing

- Diode-pumped laser head burn in
- Canister seal testing
- Canister/optical bench vibration testing

→

LOM & LEU qualification testing

- Burn-in
- Thermal/vac seal test
- Vibration testing
- Operational vacuum testing

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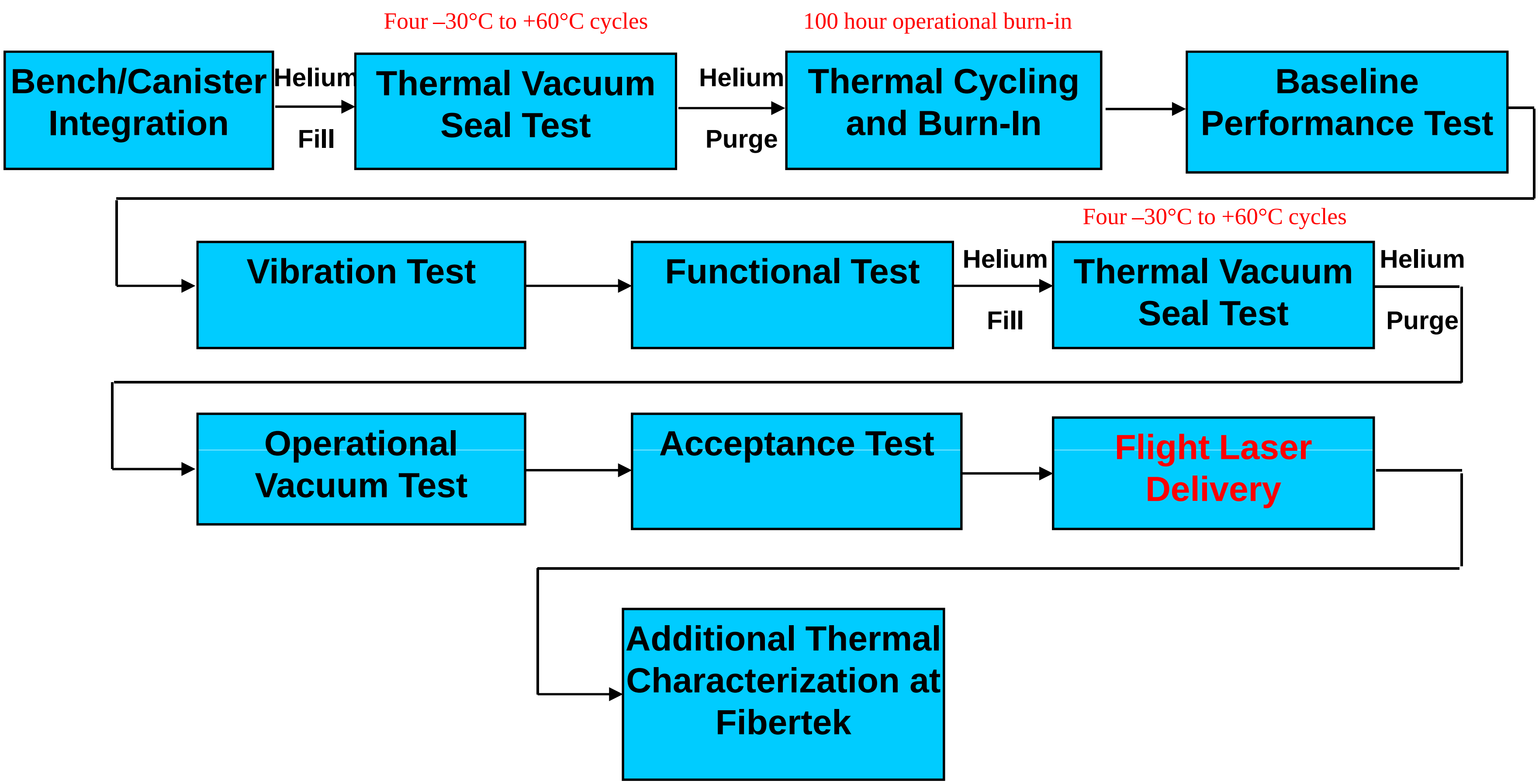
Laser Optics Module Qualification

Qualification Flow Plan



Both laser's outputs were unchanged at the end of full space-qualification testing

Laser Build & Qualification Issues

- **Space-qualified electronics were more expensive to build and test than anticipated**
  - **Use of radiation hard parts required complete redesigns of previously used electronics**
  - **Laser Electronics Unit test plan required almost 2 man years of effort to develop**
    - **Software Flight Qualification Test was more extensive than originally planned to meet NASA requirements**
    - **Software test procedure alone was >70 pages and was executed 5 times**
- **Conducted EMI due to pulsed power draw required addition of large EMI filter by Ball**
- **Subtle power supply changes surfaced intermittent start up glitches after space craft integration and required modification to the Laser Control Board**

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Space-Qualifiable Laser Design Guidelines

- 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 in conjunction with Ball Aerospace and NASA with 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**

Orbital Laser Performance

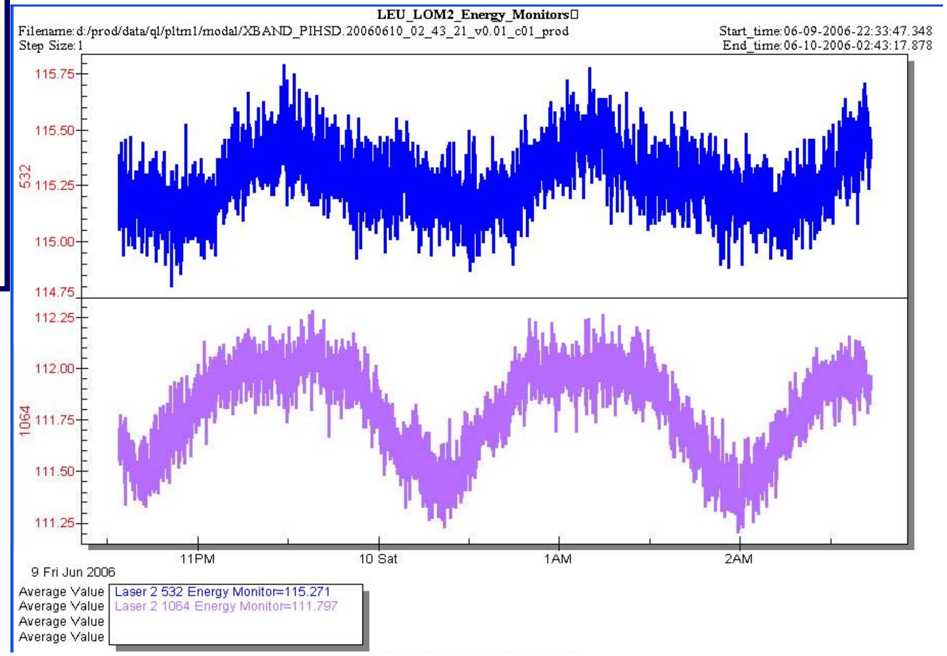
- CALIPSO launched on April 28, 2006
- Health of the electronics and internal pressure verified for both lasers ~ 2 weeks later
- Laser #2 was successfully operated at full power on May 23
  - Total power unchanged, small balancing of 1064 nm/532 nm needed
  - A lidar ground return was observed without on orbit alignment of the laser transmitter assembly pointing.
- The laser was shutdown to allow final orbit correction maneuvers and was restarted June 6 after the satellite had entered the A-Train
  - Final laser and lidar alignments performed week of June 5
- First lidar data released June 9

Short Term On Orbit Stability

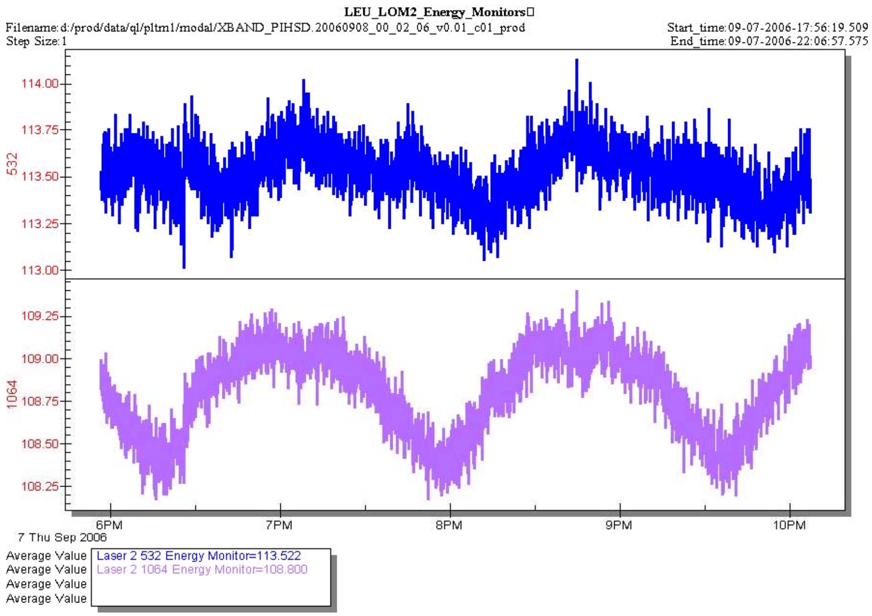
Dual wavelength energy monitor

- high precision measurements of both 532 nm and 1064 nm shot to shot energies
- On orbit shot to shot energy stability is ~0.3%
- < 0.1% energy trends can be measured with modest averaging

June 10, 2006 energy monitor



Sept. 7, 2007 energy monitor data



Oscillations in the energy monitor data are due to orbital temperature variation. Peak to peak value of oscillations are ~1 mJ.

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Laser Energy Trends

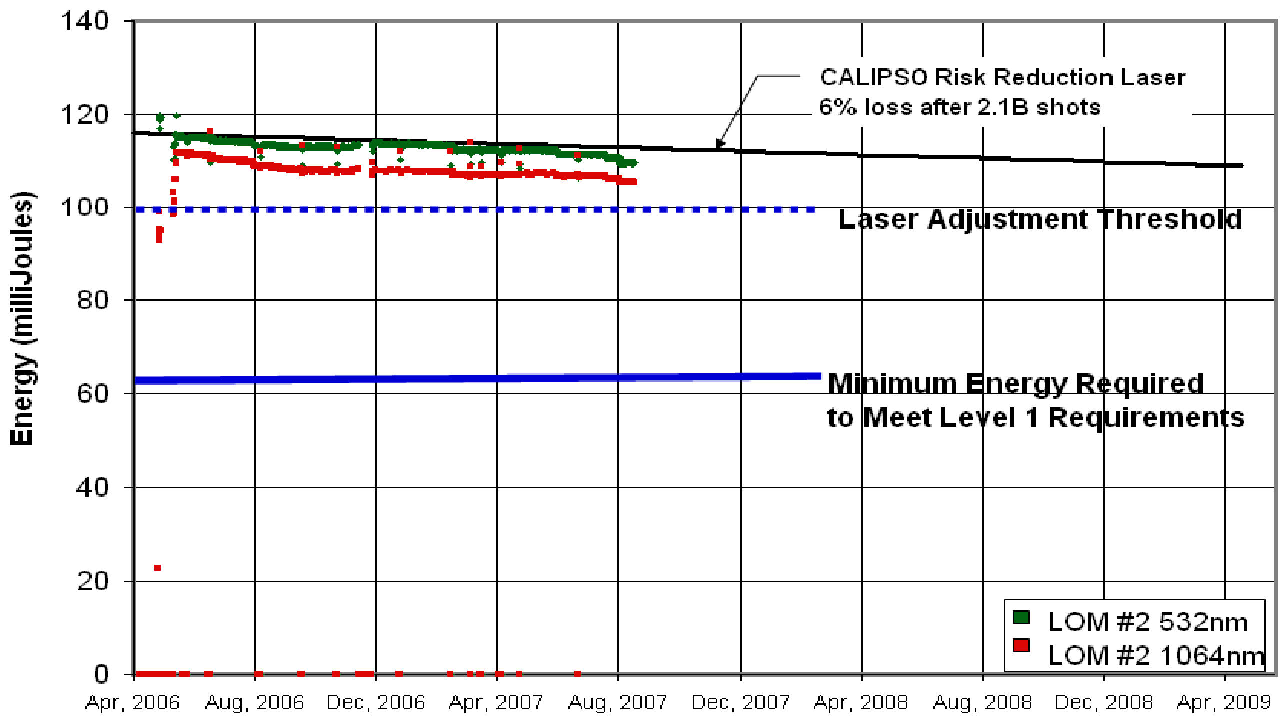
Total laser energy is down 5.2% since lidar commissioning in early June 2006

- **From 6/06/06 to 9/9/07 the total energy dropped from 227.0 mJ to 215.2 mJ**
- **4.2% per year energy decrease is consistent with pre-launch life testing**

Over half of energy drop is due to 6 bar drop outs

- **Non-catastrophic dropouts expected**

Total on orbit shot count is over 750 million



Energy Decrease Details

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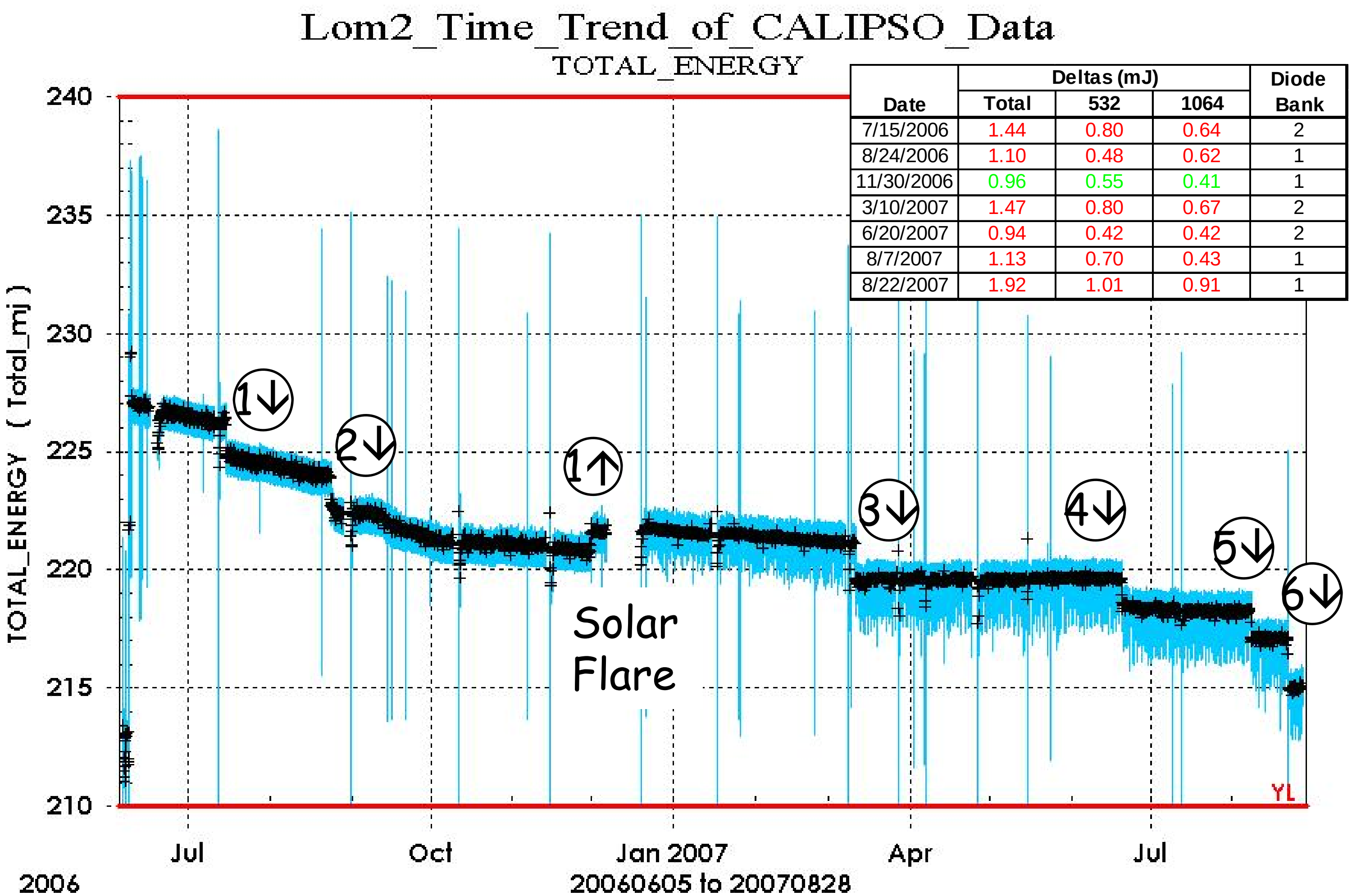

Date	Deltas (mJ) Total	532	1064	Diode Bank
7/15/2006	1.44	0.80	0.64	2
8/24/2006	1.10	0.48	0.62	1
11/30/2006	0.96	0.55	0.41	1
3/10/2007	1.47	0.80	0.67	2
6/20/2007	0.94	0.42	0.42	2
8/7/2007	1.13	0.70	0.43	1
8/22/2007	1.92	1.01	0.91	1

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Compensation for Energy Decrease

- **Total energy decrease to date is equivalent to loss of 10 of 192 diode bars**
- **Diode pump pulse width ground control commandable**
  - **Current value is 144 µs**
  - **Increase to to over 200 µs possible**
- **Diode temperature is off optimum for better λ match to etalon in 532 nm receiver channel**
  - **Cooler operation can increase output energies**

Laser Modeling Results

Total Energy (mJ)	# of Bars	Pedestal Temp (°C)	Pulse Width (µS)
215	182	17.3	144
230	182	17.3	154
220	182	15.45	144

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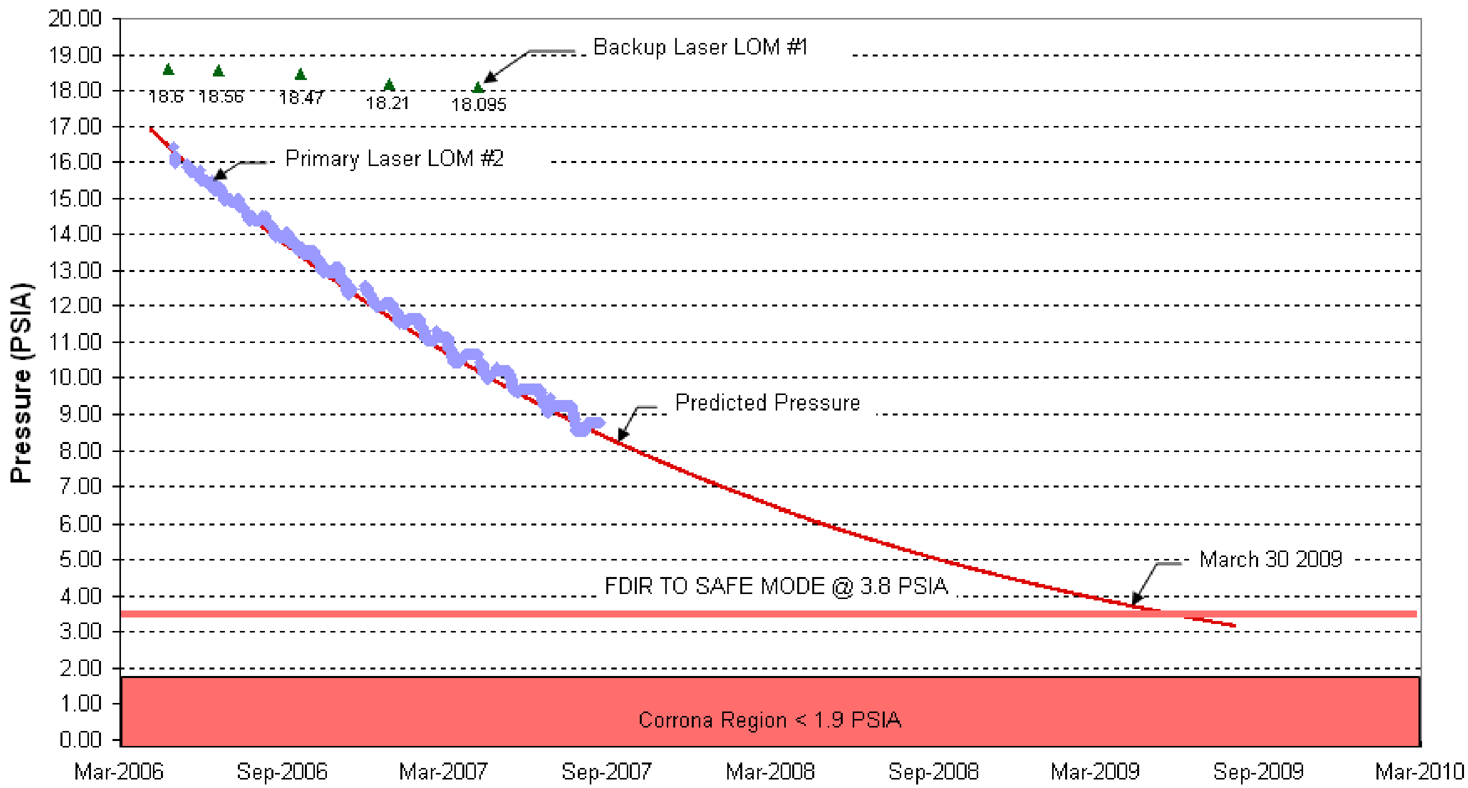
Laser Canister Pressure Trends

Pressure loss will limit on orbit life of Laser SN #2

- **Pressure trend fit predicts ~3 years to 2X corona limit**
- **Meets planned mission life of 3 years**

Laser SN #1 pressure trend exceeds planned mission life

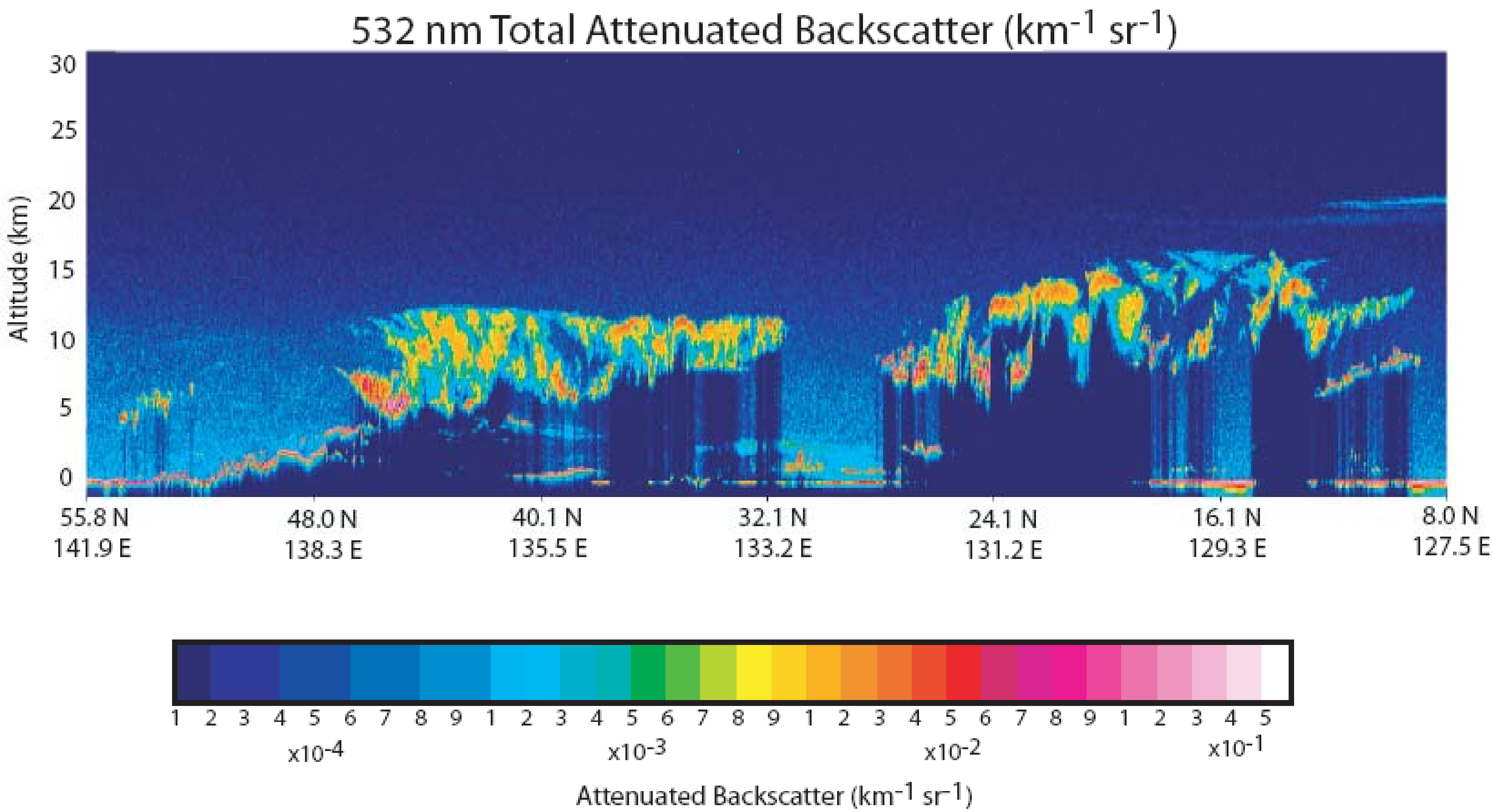
- **Pressure decrease is < 3% in 15 months**



September 7, 2007

CALIPSO 'First-Light' Lidar Measurements

7 June 2006



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