Applications of Fiber Amplifiers for Space:
Laser Altimetry and Mapping

The First ESA-NASA Working Meeting on Optoelectronics:
- Fiber Optic System Technologies in Space

ESTEC/ESA
Noordwijk, The Netherlands

D. Barry Coyle
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Presentation Flow…

Lasers in space
- NASA applications
- Current work @ NASA-Goddard

Flight Qualification
- brief history
- what's been successful (and not)
- state of the art

Fiber-based transmitters
- impact and potential
- efforts @ NASA
- work to do

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Seeded Fiber Amplifier Outline for Remote Sensing

Tunable: Rep Rate
Pulse Width
Pulse Shape
Pulse Energy

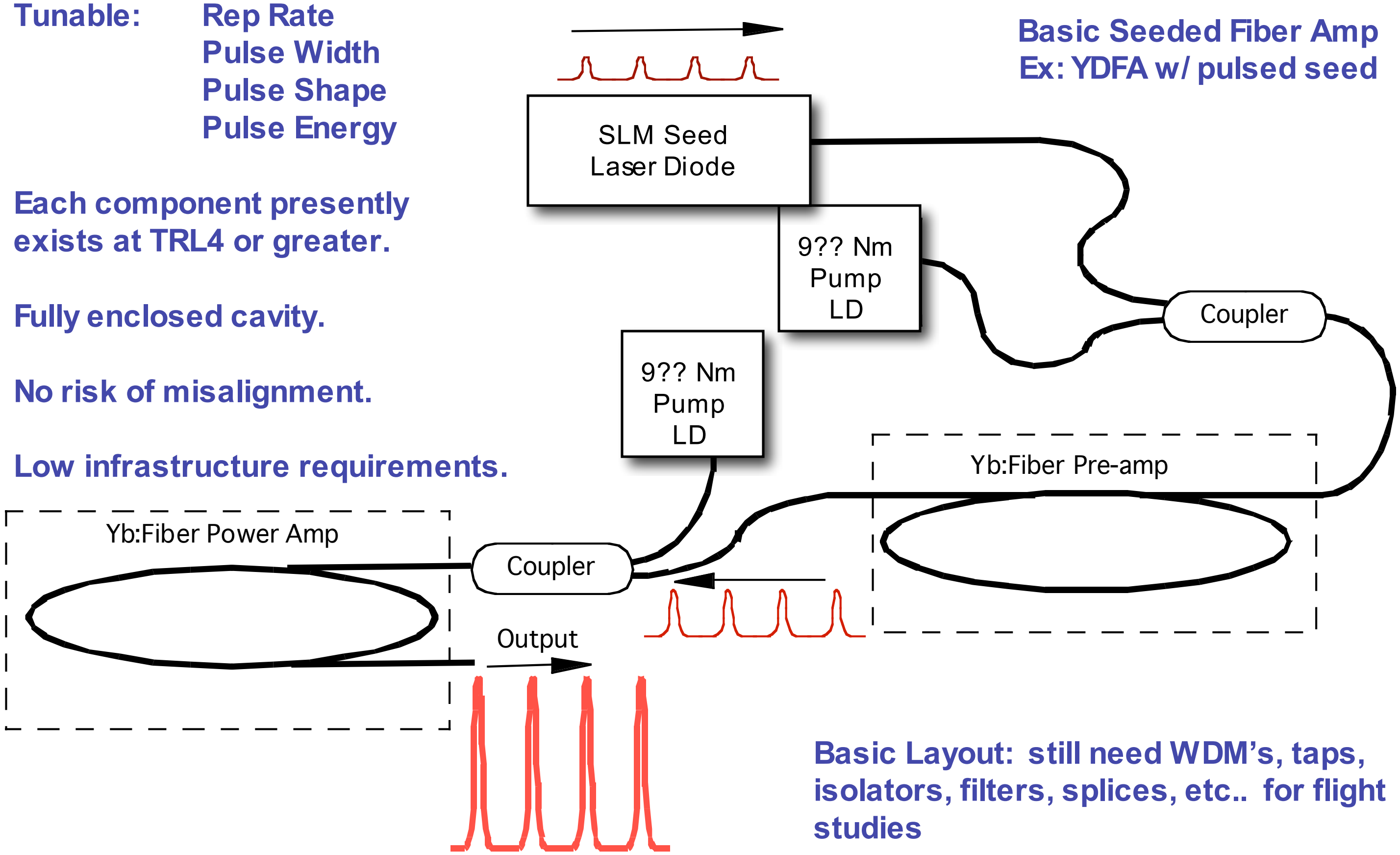
Basic Seeded Fiber Amp
Ex: YDFA w/ pulsed seed

Each component presently exists at TRL4 or greater.

Fully enclosed cavity.

No risk of misalignment.

Low infrastructure requirements.



Basic Layout: still need WDM's, taps, isolators, filters, splices, etc.. for flight studies

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Potential Flight Fiber Amplifier/Laser Applications

-**Altimetry**
-Atmospheric Lidar (DIAL)
-**Wind Lidar**
-**CO_2 Lidar**
-**Water Vapor Lidar**
-Ice/**Vegaetation**/Volcanic Activities
-Bathymetry
-Metrology
-**Telecom/Transponders**
-**Robotic Service & Docking**
-Automated Planetary Rovers

Actively pursued work at GSFC is in **bold.**

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Flight applications:

Mars Laser Sounder for Global Water Vapor Measurements

Graham Allen (gallan@pop900.gsfc.nasa.gov)

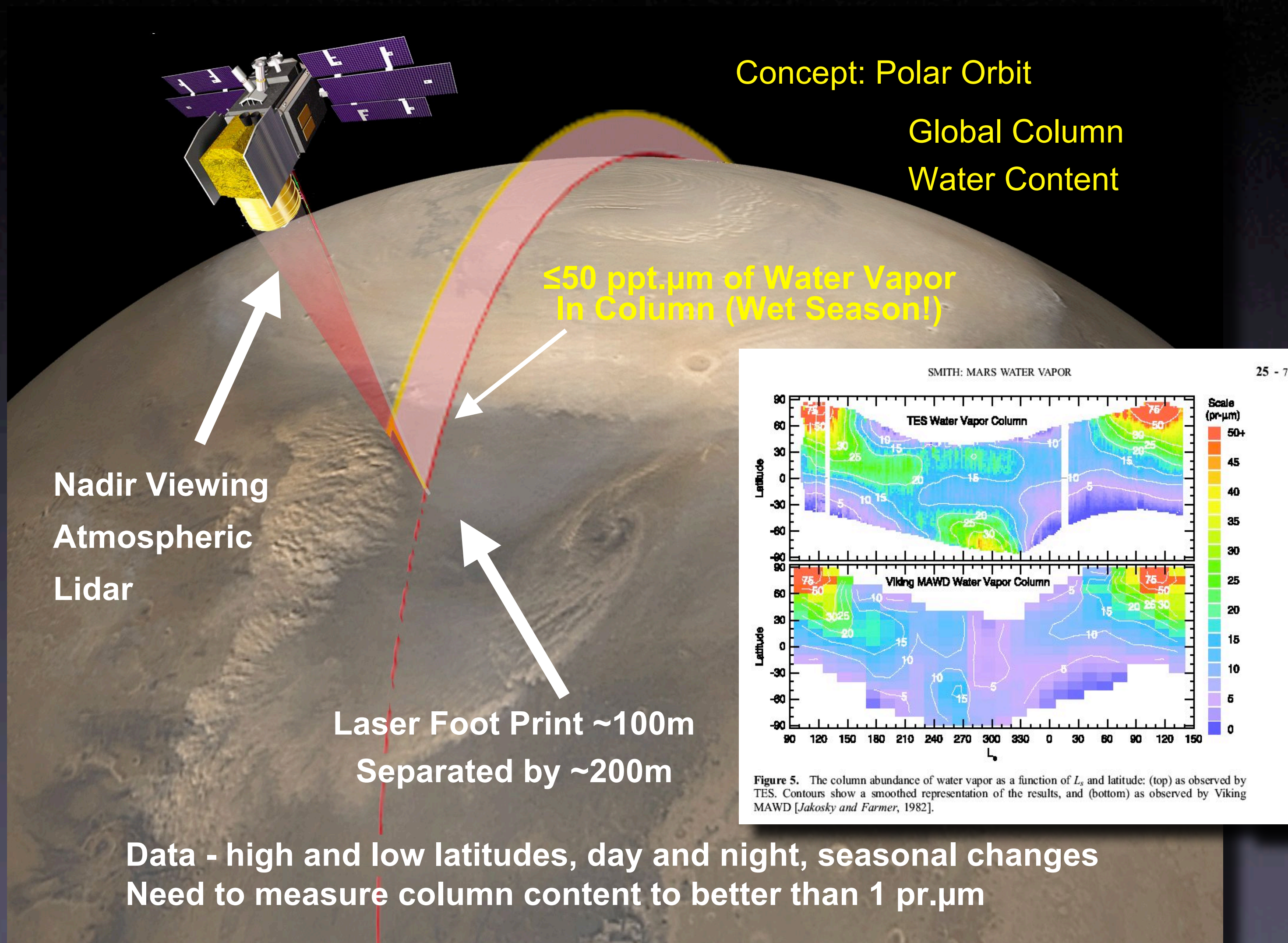

Figure 5. The column abundance of water vapor as a function of L_s and latitude: (top) as observed by TES. Contours show a smoothed representation of the results, and (bottom) as observed by Viking MAWD [*Jakosky and Farmer*, 1982].

Data - high and low latitudes, day and night, seasonal changes
Need to measure column content to better than 1 pr.µm

Flight applications:

Mars Laser Sounder for Global Water Vapor Measurements

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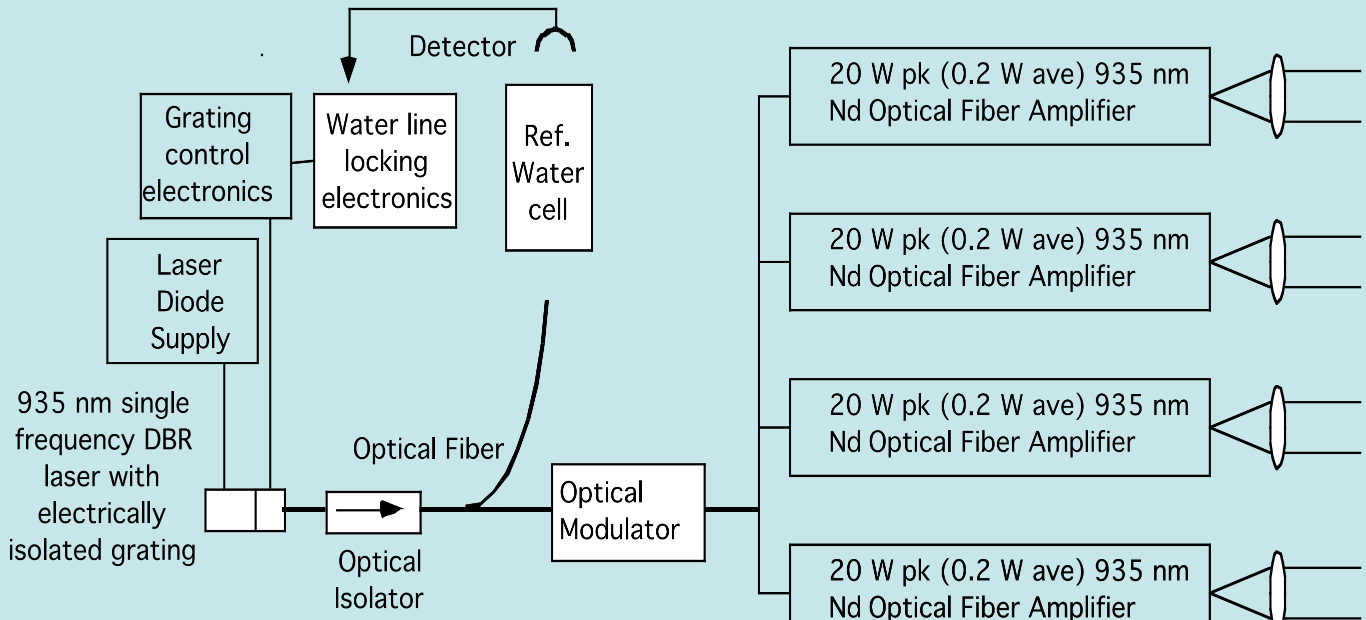
Master Oscillator Power Amplifier(s)



Fiber Amp technology is an enabling technology for a new class of planetary atmospheric instruments based on LIDAR.

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Flight applications:

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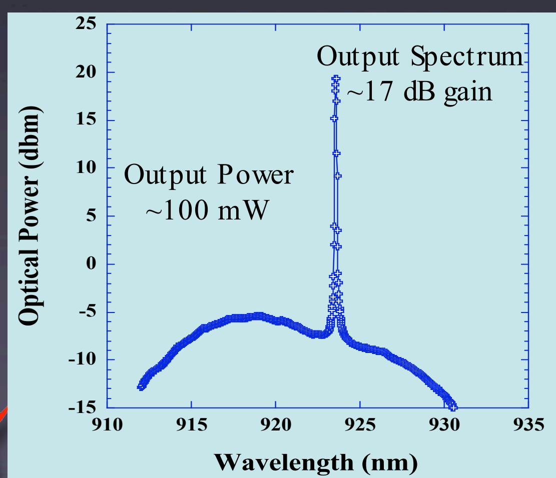
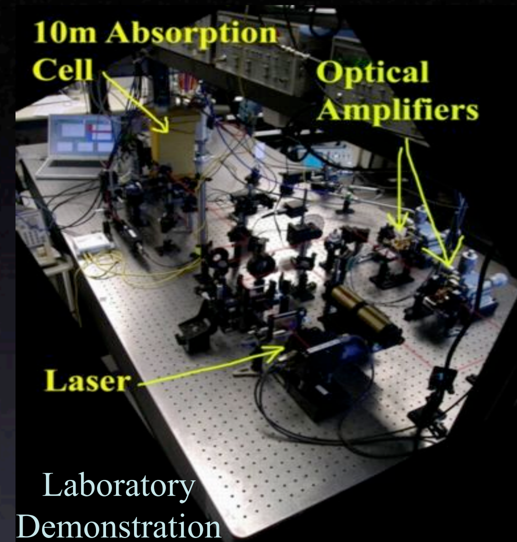
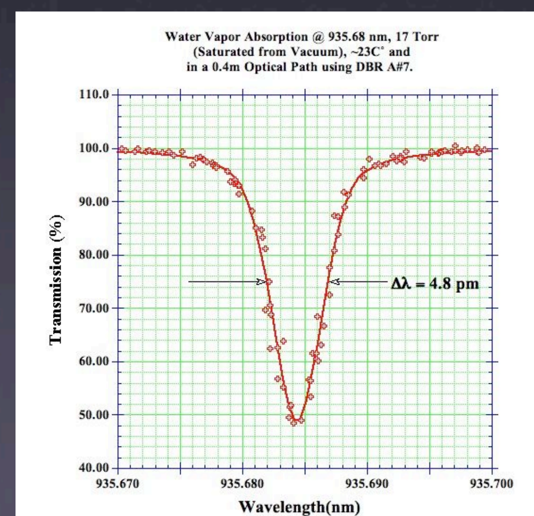
Requires narrow pass filter to eliminate ASE and improve SNR.





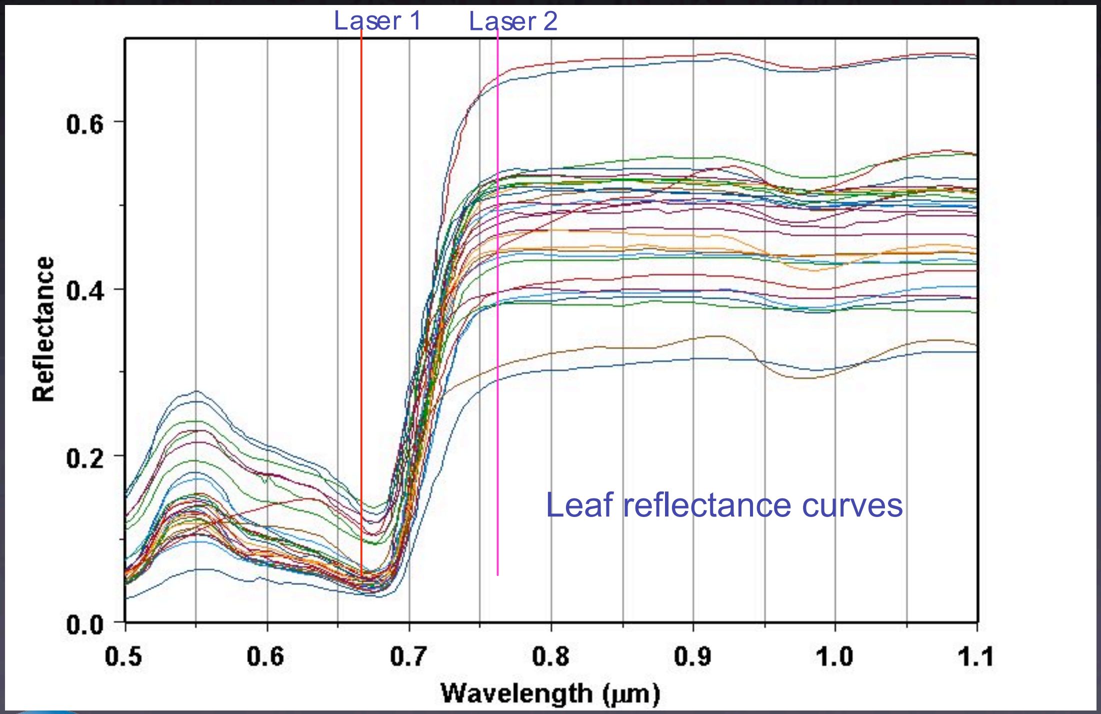


Flight applications:

Spectral Ratio Biospheric Lidar

Jonathan Rall (jonathan.a.rall@nasa.gov)
Robert Knox (knox@spruce.gsfc.nasa.gov)

Spectra from healthy leaves show a characteristic difference between red and near-IR reflectance



Leaf and bark spectra are from the Superior National Forest (Hall et al. 1992. NASA TM 104568)

- All green vegetation exhibits "red edge" due to chlorophyl absorption @ 680 nm
- Passive instruments are broadband and susceptible to atmospheric effects and trace gas absorption
- Differential reflectance measurement can improve NDVI-type measurements using two lasers:
  - 670 nm (Red)
  - 780 nm (NIR)

Flight applications:

Spectral Ratio Biospheric Lidar

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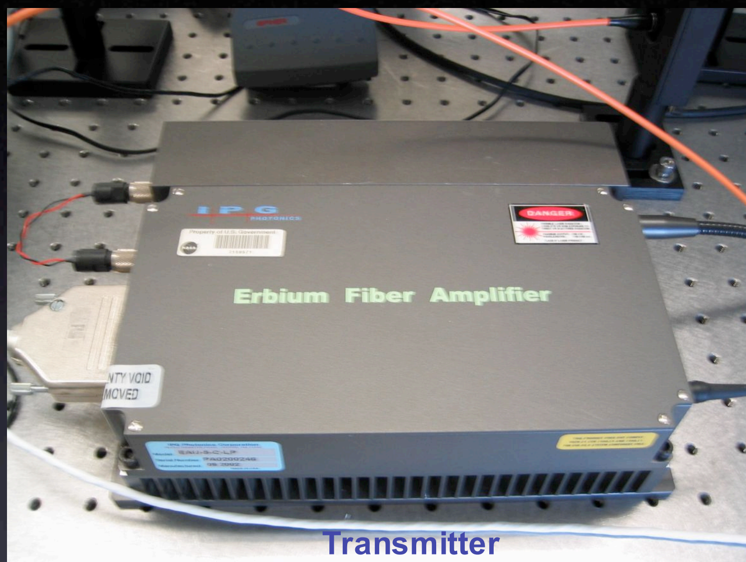

- Dual semiconductor laser transmitters
  - 660 nm / 40 mW
  - 780 nm / 70 mW
- 5 Watt Erbium doped fiber amp
  - 1540-1570 nm - flat gain curve
  - Polarized single mode input
  - Polarized output - improves freq doubling effic
- Periodically Poled KTP crystal
  - Efficient (>30%) frequency doubling
  - 1570 nm -> 785 nm

- 20 cm diameter Schmidt-Cassegrain telescope
- Dichroic beam splitter, splits received light into 660 nm & 780 nm channels
- Fiber-coupled single photon counting modules
- EG&G Turbo Multichannel Scaler w / PC
- 5 ns gate time @ 800 bins

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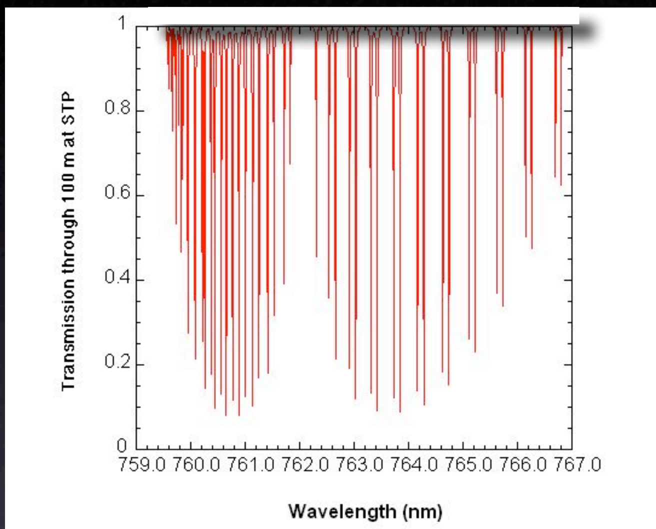
Flight applications:

Atmospheric O_2 Lidar: P & T Measurement

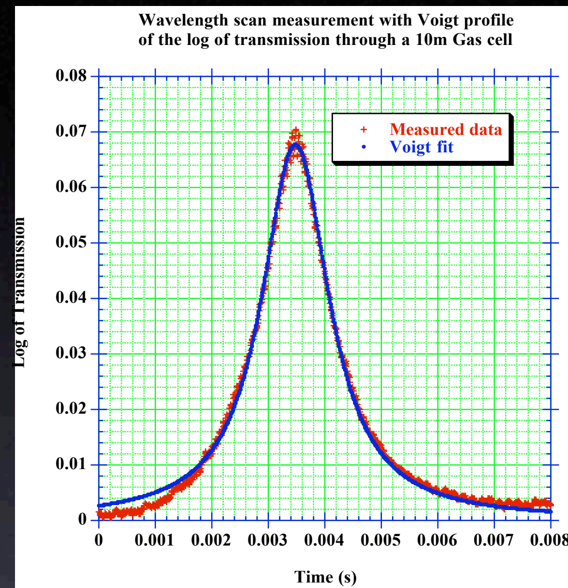
Mark Stephen (mark.a.stephen@nasa.gov)



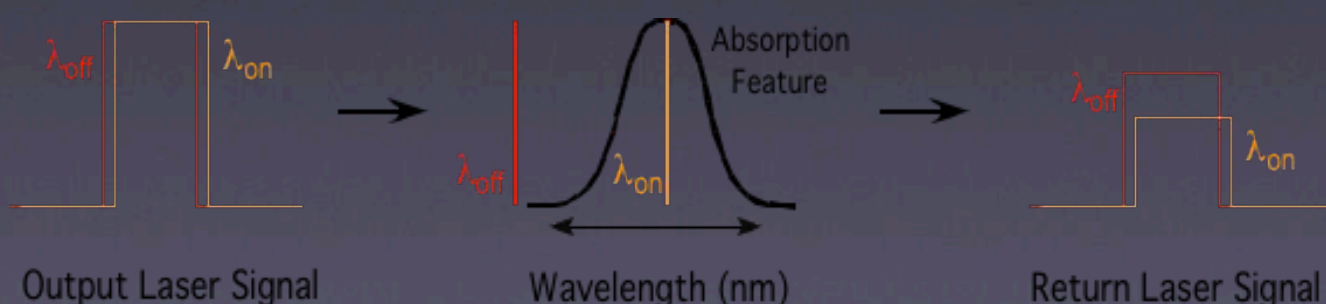
Calculated atmospheric transmission for 100 m path at STP (763.3 nm used for development, weaker lines from a/c or spacecraft to avoid saturation.)

Advantages of Oxygen A-Band for Pressure Measurement

- Oxygen is well-mixed in Earth's atmosphere
- Free of atmospheric contamination
- Others have used this spectral region and measured pressure to ~ 1 mbar and temperature to 1°C accuracy
- Silicon detector efficiency is optimized in near IR
- Excellent fiber laser sources are now available



With continuous scanning, we can distinguish between the temp. and press. broadening processes with Voigt profiles; a convolution of Lorentzian and Gaussian functions.



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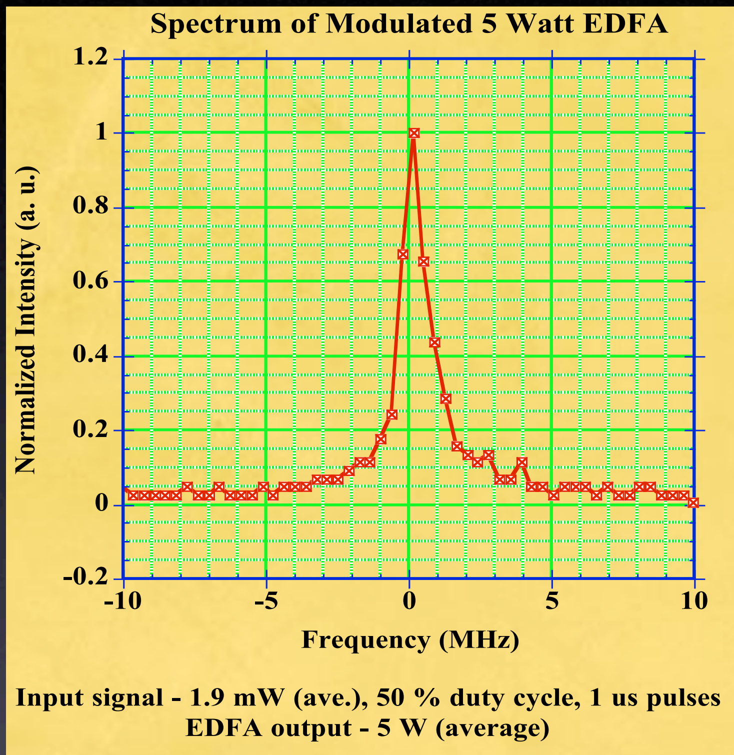

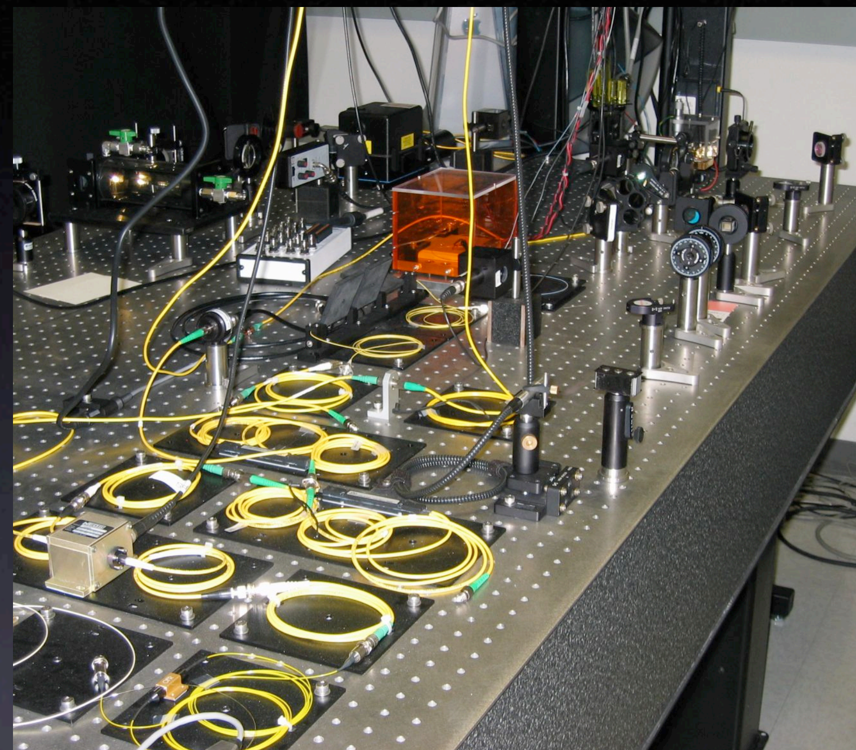

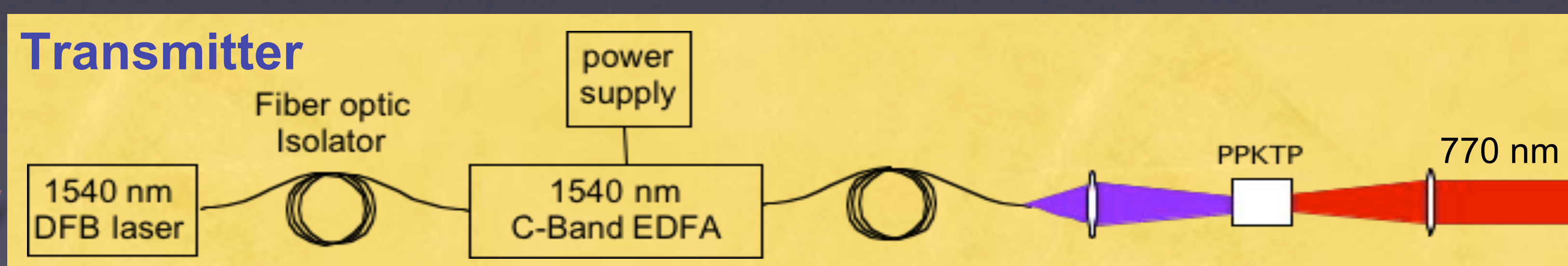

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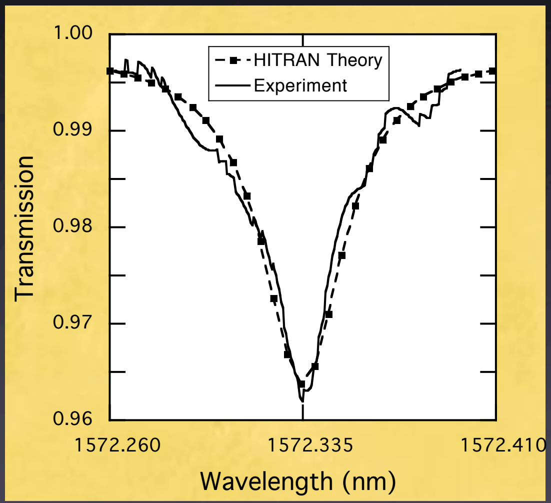
Flight applications:

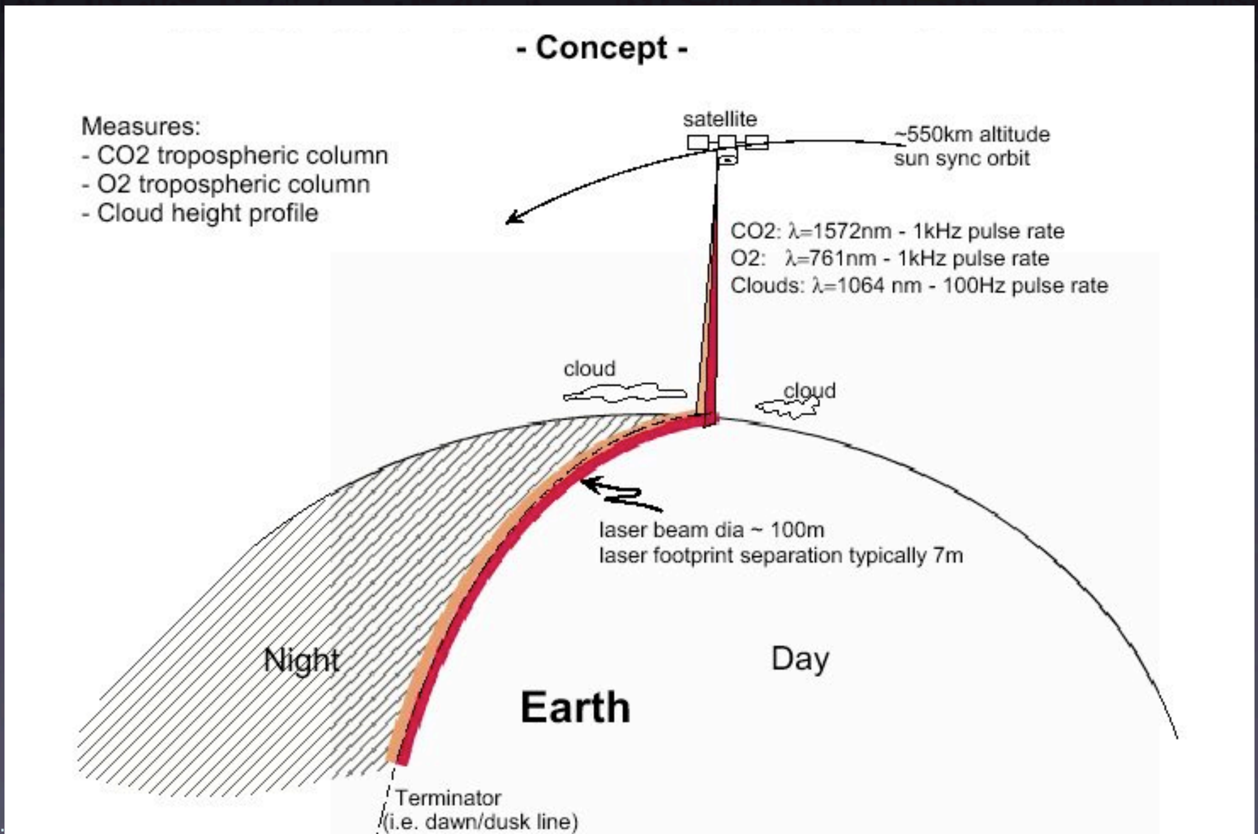
CO_2 Lidar

Mike Krainak (mkrainak@pop500.gsfc.nasa.gov)

- **Developing and demonstrating a technique & core technology to remotely measure CO_2 concentrations from space**
- **Addresses a top priority for studies of the Earth's carbon cycle**
- **Leveraging telecom Fiber amplifier development partnerships.**



HITRAN theory & data @ NASA-GSFC. A 1-way path of 206 m, on 11/21/02 @ 4:50 pm EST..



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Flight applications:

CO_2 Lidar

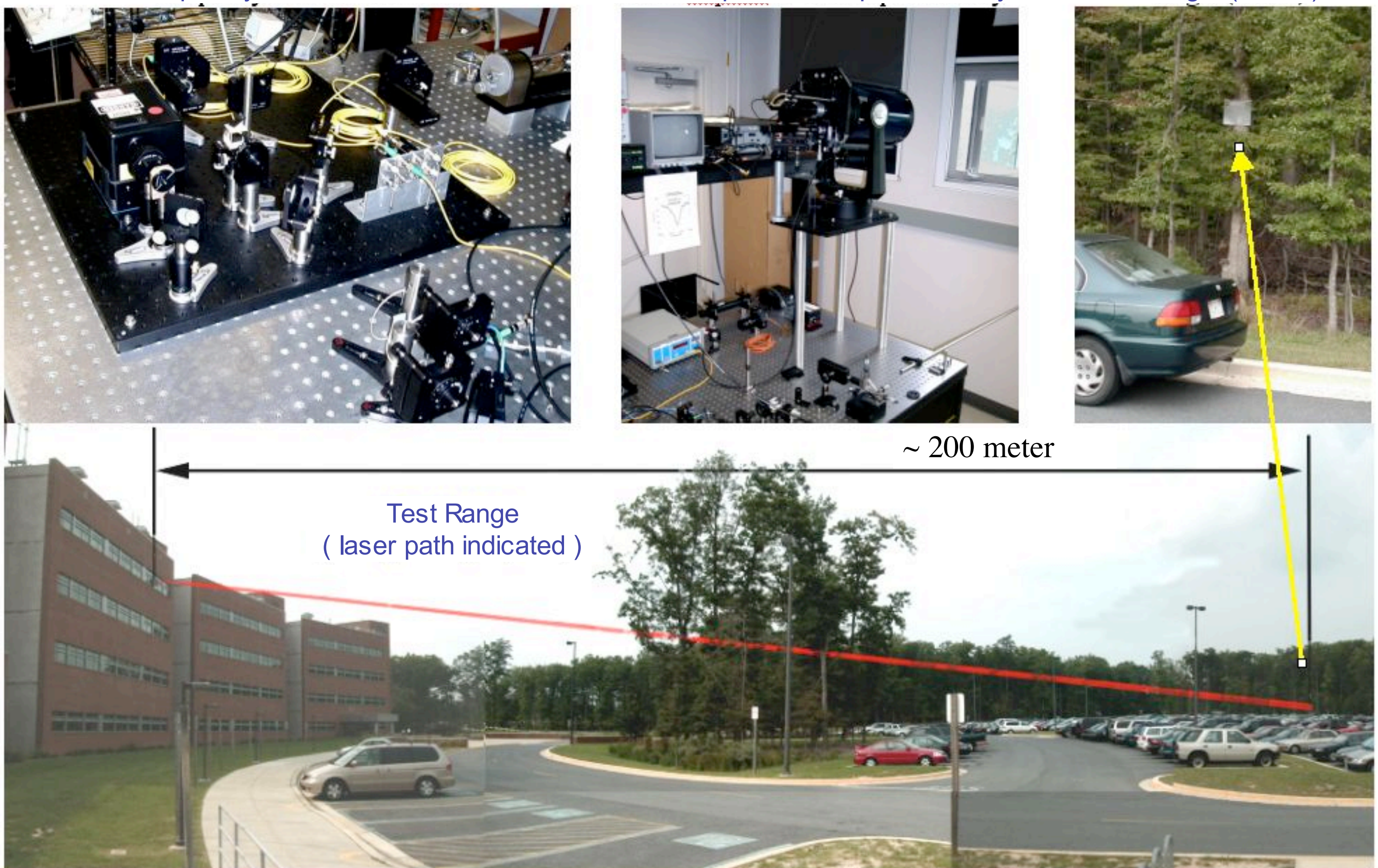
Mike Krainak (mkrainak@pop500.gsfc.nasa.gov)

Open Path Atmospheric CO_2 Measurement: 206 m Test

Frequency Tunable Diode Laser

Fiber Amp & Telescope Assembly

Target (in tree)



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Flight applications:

CO_2 Lidar

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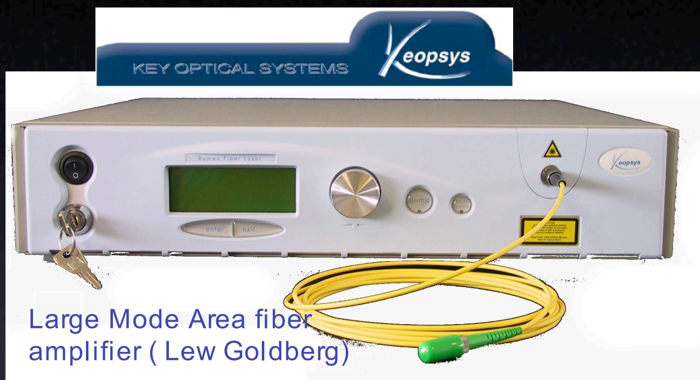
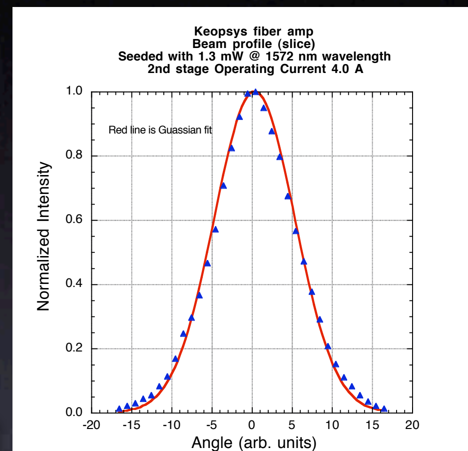
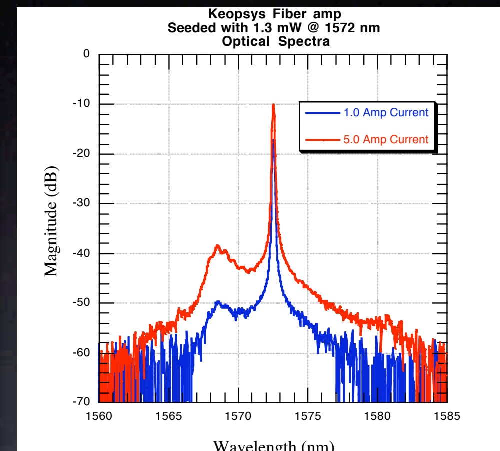
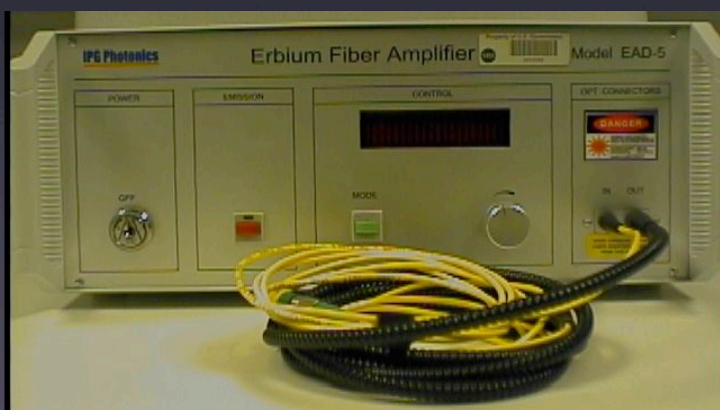
Er Fiber Amplifier Candidates for achieving Aircraft or Space CO_2 Link



Large Mode Area fiber amplifier (Lew Goldberg)







- Amplifies tunable seed laser at 1572 nm CO2 gas absorption line
- Produces 5 W output from 1 mW seed laser input
- Uses Erbium fiber amplifier developed for fiber optic telecommunications
- Rugged & all solid state
- 8% wall plug efficiency with commercial electronics

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NASA Technology Readiness Levels (TRL)

Basic Tech Research

- ***Level 1*** Basic principles observed and reported

Research to Prove Feasibility

- ***Level 2*** Technology concept and/or application formulated
- ***Level 3*** Analytical & experimental critical function and/or characteristic proof-of-concept.

Technology Development

- ***Level 4*** Component and/or breadboard validation in laboratory environment.

Technology Demonstration

- ***Level 5*** Component and/or breadboard validation in relevant environment.
- ***Level 6*** System/subsystem model or prototype demonstration in a relevant environment (ground or space)

System/Subsystem Development

- ***Level 7*** System prototype demonstration in a space environment

System Test, Launch and Operations

- ***Level 8*** Actual system completed and "flight qualified" through test and demonstration (ground or space).
- ***Level 9*** Actual system "flight proven" through successful mission operations.

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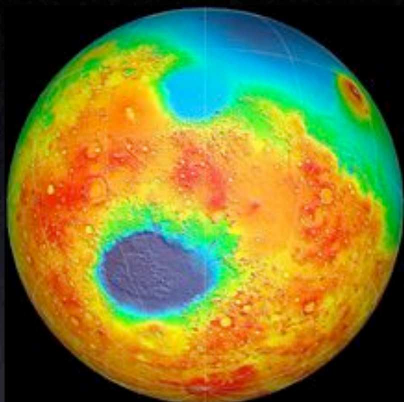
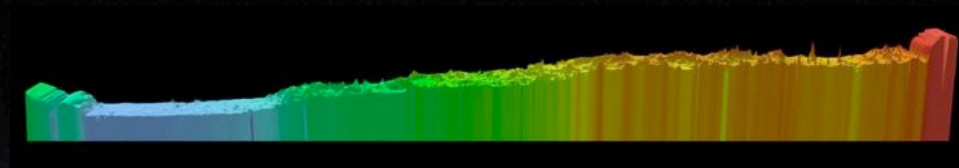
Some NASA Flight Laser Heritage





- Apollo 15, 16, & 17 lunar lander altimeter; flashlamp/Ruby
  ~ 5,000 shots / 3 lasers, (1971 - 1972)
- Mars Orbital Laser Altimeter (MOLA)
  ~ 670 x 10^6 shots, (1996 - 2000)
- Clementine (LLNL/NRL)
  ~ 72 x 10^3 shots @ lunar surface (1994)
- Geoscience Laser Altimeter System (GLAS)
  ~ 900 x 10^6 shots / 3 lasers. (2003 - present)
- Near Earth Asteroid Rendezvous (NEAR)
  ~ 11 x 10^6 shots, (1996 - 2001)
- Mercury Laser Altimeter (MLA); DP:Nd:YAG
  ~ TBD (on route to Mercury), (2004 - 2012)
- Shuttle Laser Altimeter (SLA- 01 & 02)
  < 10 x 10^6 shots(?), (1995 - 1998)
- Laser Vegetation Imaging Sensor (LVIS) (1995 - present)
  Aircraft system(s) precursor for flight instrument
- Lunar Orbital Laser Altimeter (LOLA)
  TBD (launch in 2008)

Note: All lasers were diode pumped
Nd:YAG systems unless specified

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Initial Considerations For Space Flight Laser Designs: Selected Efforts

Near-Term Science Applications:

Wind/Atmospheric LIDAR [1 J/pulse @ 100 Hz]
Vegetation/Ice/Topography [15 - 25 mJ/pulse @ 300 Hz]
High Res Vegetation [1 - 10 mJ/pulse @ 10 - 100 kHz]

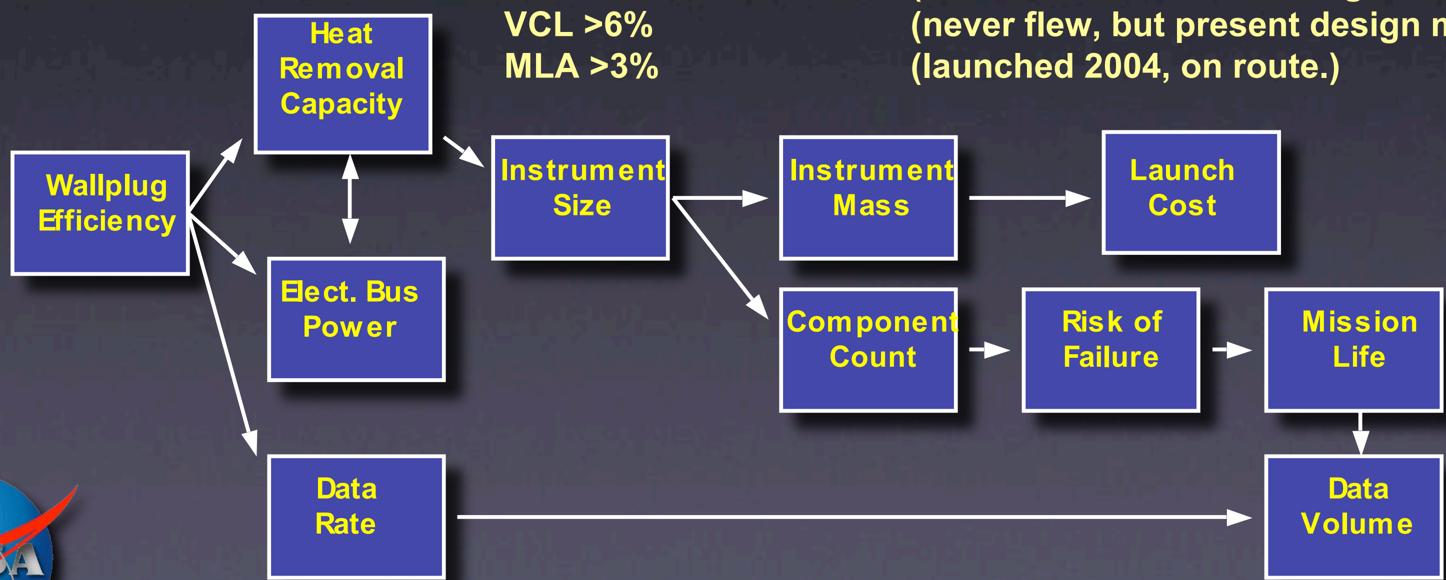
Our efforts *must* improve, with some significance, one of the following solid state laser tech issues:

- Efficiency (optical, wallplug)
- Reliability (damage, lifetime)
- Ruggedness (alignment, cleanliness)

Efficiency is THE big weakness:

Examples…

GLAS ~ 3% (MOPA design - effic not major concern)
MOLA >2% (multi-mode laser - effic high at time)
VCL >6% (never flew, but present design measured)
MLA >3% (launched 2004, on route.)



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Thus, a 10% efficient laser source used as a V.2 for any of these missions would immediately produce a minimum of ≥ 100% (2X) improvement in performance!

Commercial fiber amps are typically ≥ 10% wallplug efficient, using off-the-shelf non-optimized drive electronics. Flight electronics would greatly help here.

Thus: LARGE potential here for remote sensing science with fiber amps.

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Achieving Flight Laser Status

There must be a scientific customer with long term plans to justify the high cost developing the technology to the TRL needed to propose for a mission.

Lasers “seem” to be the only flight instruments that do NOT meet the TRL standards of Phase A Mission Awards. Typically, TRL4 or above exists for any instrument proposed for orbital or planetary missions.

Laser transmitters for space applications have had a “waiver” for years. *This practice needs to stop.*

“Laser” in your mission title can have a “negative implications”.

Fiber-based laser sources can raise the bar for laser transmitter reliability and performance expectations, especially for diode pumped solid-state altimetry applications.

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Cavity vs Fiber Lasers

Advantages in Capabilities

Laser Pulse Source	PRF	Pulse E	Pulsewidth	Polarization	Beam Quality
Cavity	√	√	√	√	
Fiber	√		√		√

Laser Pulse Source	Efficiency	Alignment Stability	Lifetime	Contamination	Cost
Cavity					
Fiber	√ √ !	√ √ !	√	√ √ !	√

Summary: Fiber-based laser sources have critical advantages that warrant immediate study and flight development investments.

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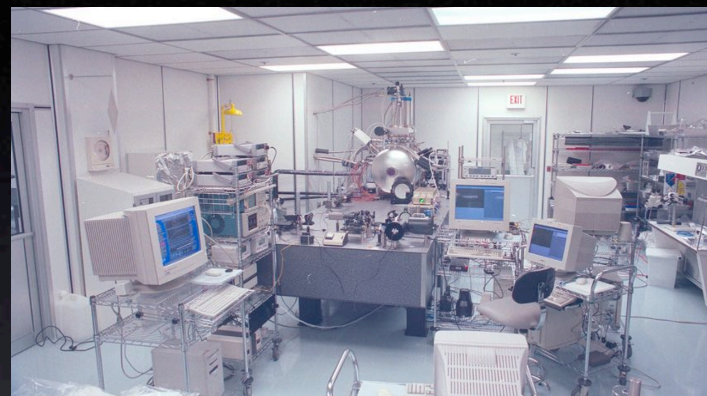
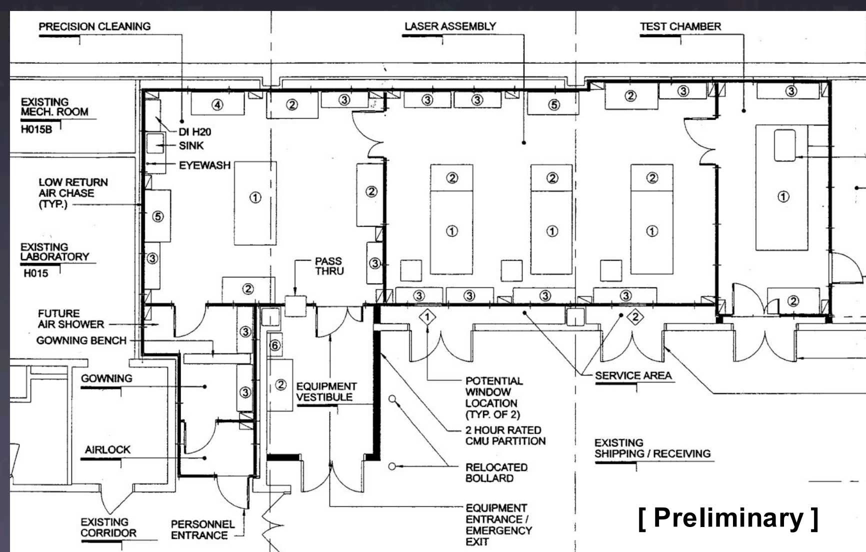
Open-Cavity vs Fiber Lasers

Infrastructure Costs





Class 100 - 10,000
Clean Room Facilities

Extreme costs and effort must be incurred when producing flight quality, open-cavity lasers.

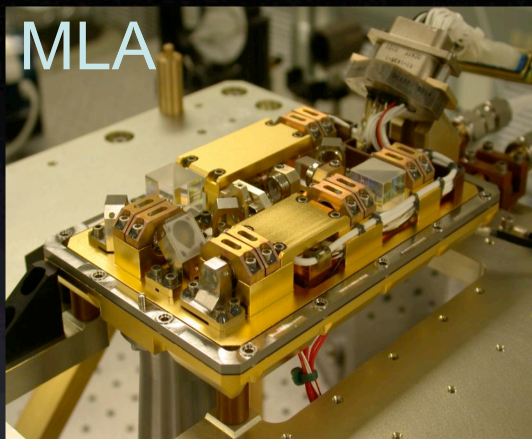
New facility is under development @ GSFC for LOLA and future flight lasers.

Present estimates are:
~ \$145/ft^2 (\$1,561/m^2)
@ 1500 ft^2 (139 m^2)
= \$217 K/year.

…in order to maintain proper clean room operation.
(Does not include project specific expertise)

Rob Taminelli:
(rtaminelli@msmail.gsfc.nasa.gov)

NASA-GSFC Flight Laser Altimeter Heritage: a sample



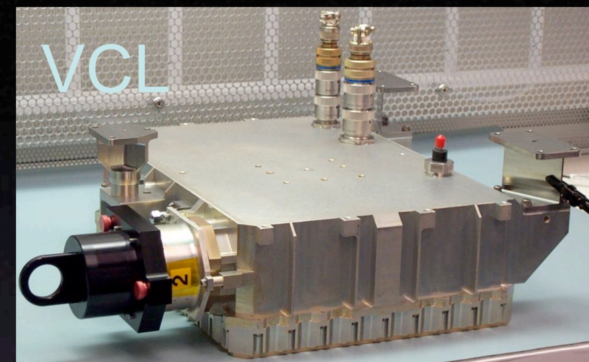
Mercury Laser Altimeter
0.2 W (2W capable)

Geodynamic Laser Altimeter System
4 W

All of these were:
- Pulsed, diode pumped Nd:YAG
- Profiling laser altimeter
- Built or managed by GSFC for a GSFC mission.

Only 3 of these launched successfully

All of these had significant “issues” due to:
1. the inherent complexity of a cavity-based laser,
2. lack of heritage,
3. it’s associated development requirements and costs, and
4. limited commercial cousins from which to draw knowledge and expertise.



Vegetation Canopy Lidar*
4 W

Mars Orbital Laser Altimeter
4 W

*did not fly

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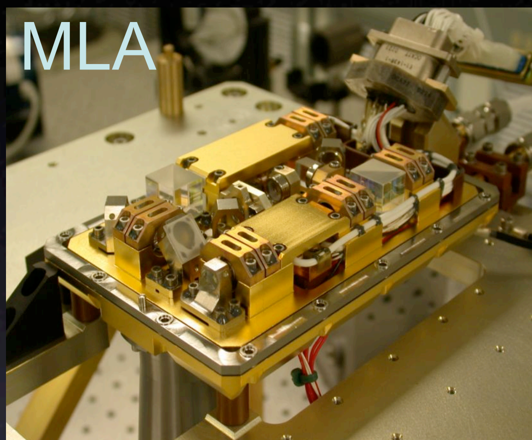
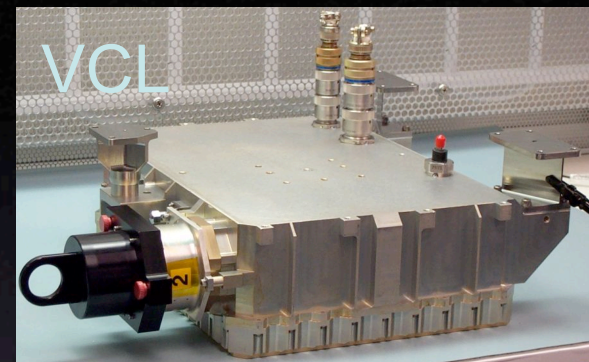
NASA-GSFC Flight Laser Altimeter Heritage: a sample



Mercury Laser Altimeter
0.2 W (2W capable)

An additional photo needs
To be added here…



Vegetation Canopy Lidar*
4 W

Geodynamic Laser Altimeter System
4 W

Pulsed Seeded
Fiber Amp

Mars Orbital Laser Altimeter
4 W

Most efficient system shown is VCL @ 6%

*did not fly

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Flight Quality Fiber Amplifier Systems can Readily be Derived From Industry

- **Areas where we benefit from the massive investments in the telecommunications industry:**
- \- Component cost
- \- Component data sets and lifetimes
- \- Telecordia NEBS testing heritage and standards
- \- New component technologies, infrastructure, competition, etc.…
- **Areas that need additional support for flight quality components:**
- \- Wavelength; most altimetry-based remote sensing is done ~ 1 um. Component selections are thin at this λ.
- \- Radiation; little or no effort has been done for radiation hardened devices. Internal efforts are underway. (M. Ott: Melanie.Ott@gsfc.nasa.gov)
- \- Pulsed systems; Telecom works in CW/modulated and WDM etc… Lifetimes and performance data is needed in pulsed modes.

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Fiber-Based Laser Altimeter "General" Requirements

Specifications for Earth or Planetary Mapping Transmitter

- 100 uJ - 1 mJ
- 1 ns - 10 ns
- 1047 nm, 1064 nm
- 100 Hz - 10 kHz

Note: Specifications for orbital pulsed waveform-capture altimetry methods. These are at the "high end" for fiber-based sources.

Requirements change with respect to the receiver technology of choice;

- PN Code, waveform capture, single photon capture, etc...

Examples:

Single photo-electron detection use MCP's, APD's, PMT's and allow for lower pulse energies but need higher rep rates and multiple samples for increased precision.

Single-shot waveform capture can use APD's gather much more information/laser shot, but need higher pulse energies.

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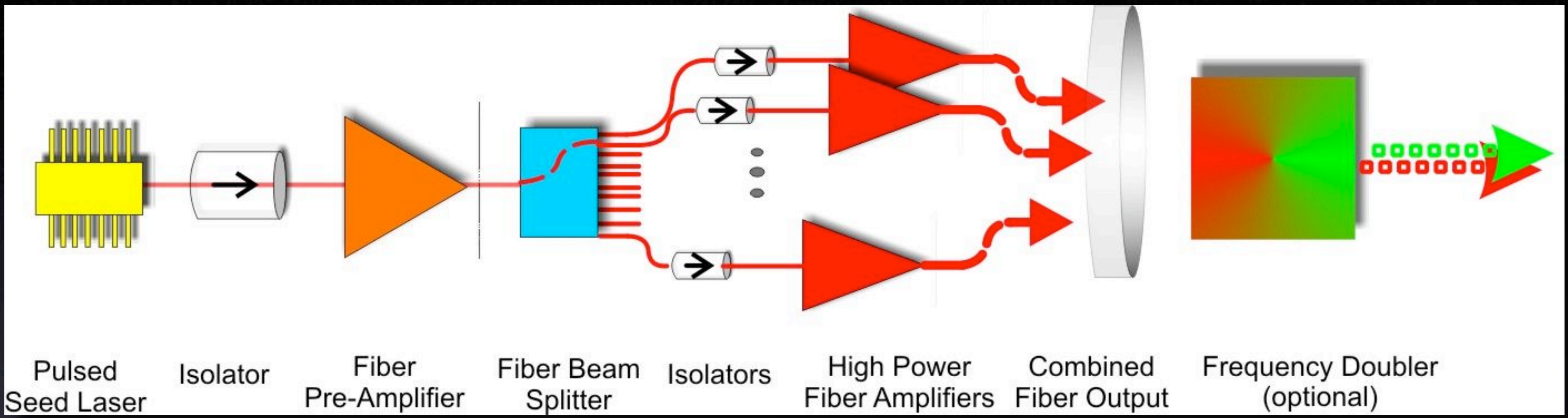
Our Fiber-Based Imaging Lidar Fundamental Scheme



Inherent advantages to fiber lidar laser transmitters over traditional solid state transmitters:

- Wavelength flexible (920-940nm, 1040-1120nm, 1530-1600nm)
- All fiber coupled for a compact, alignment insensitive, modular design
- Flexible pulse width (1ns – cw) and repetition rate (100kHz – cw)
- All semiconductor laser seed and pump lasers for high wall plug efficiency and high reliability (100,000hrs typical)
- Component development can learn much from the Telecom industry

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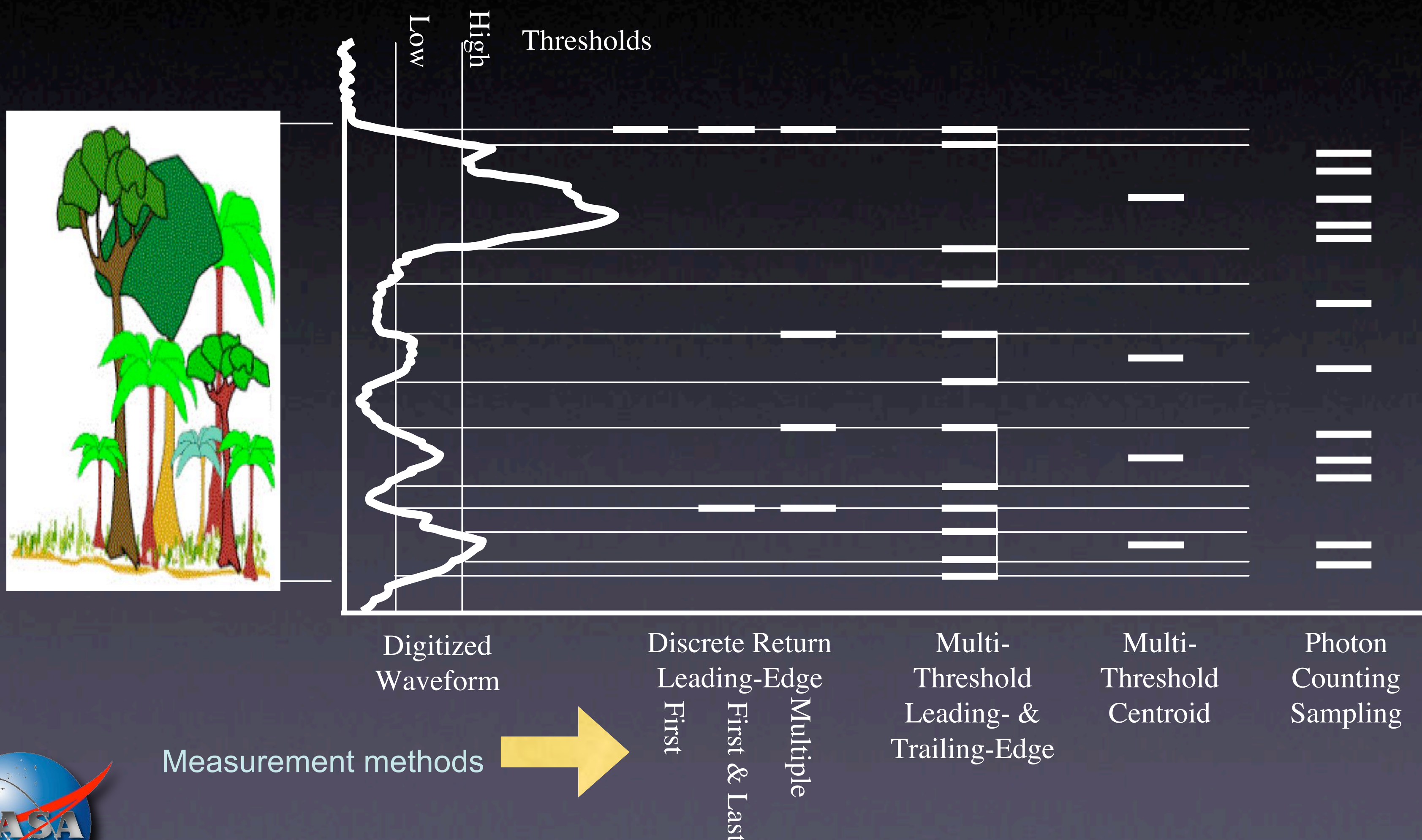
Laser Based Altimetry and Imaging Fiber Amplifier Applications Example: Earth Vegetation

Bryan Blair, (bryan@arthur.gsfc.nasa.gov)



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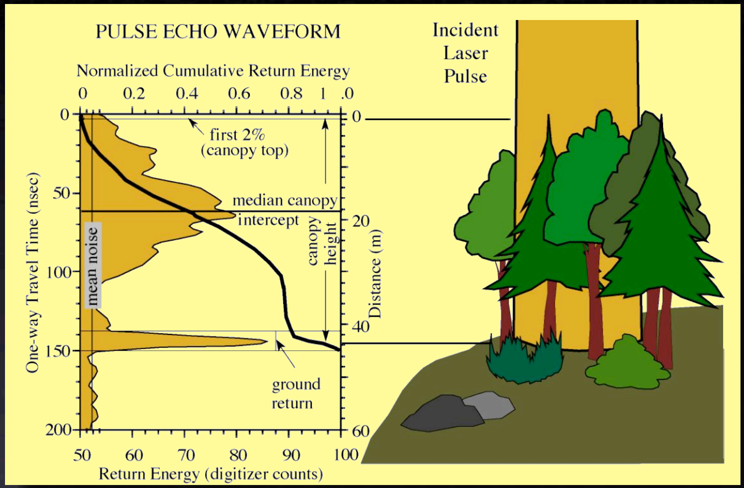
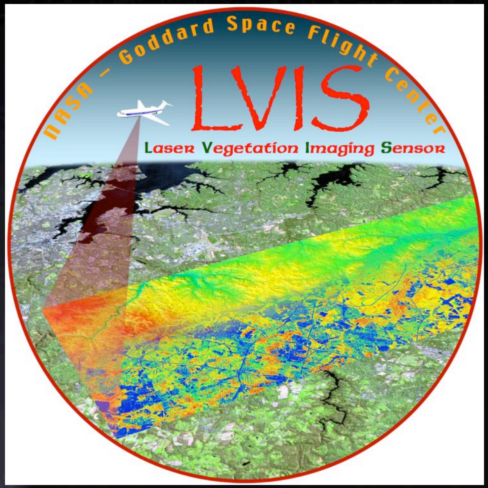




NASA's airborne Laser Vegetation Imaging System
www.lvis.gsfc.nasa.gov

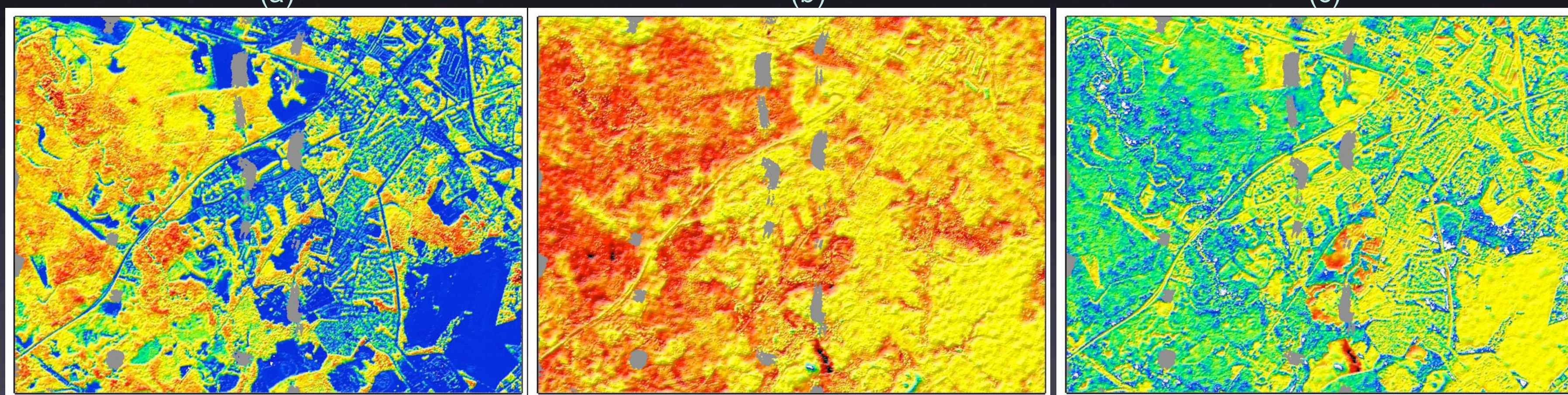
- LVIS data products compared to Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEM) are:
  - Ground elevation (lowest reflecting surface)
  - Canopy Top elevation (highest reflecting surface)
  - Elevation of median canopy intercept (where 50% of the returned energy occurs)
- LVIS capabilities:
  - Medium-altitude (10km AGL), waveform-recording lidar system.
  - Utilizes footprints approximately the size of crown diameters in order to produce images of canopy height, structure, and sub-canopy topography even in the densest forests (>99% cover).
  - 20m footprint/2km swath from 10km above ground. 1064nm wavelength.

Laser Based Altimetry and Imaging Applications Example: Earth Vegetation

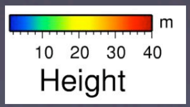
Bryan Blair, (bryan@arthur.gsfc.nasa.gov)

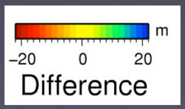
- In August 2003, LVIS was used to image a 60x18km area of the Patuxent watershed, Maryland, USA.
  - The area is a mix of ground cover types, including urban, forested (deciduous and coniferous), and agricultural land.

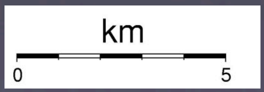
(a) (b) (c)



(a) LVIS canopy height, (b) LVIS ground minus SRTM elevation, and (c) LVIS canopy top minus SRTM elevation for a subset of the MD study area. SRTM is reflected off bare earth or vegetation structure depending on the land cover.







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Seeded Fiber Amplifier Outline for Remote Sensing

Tunable: Rep Rate
Pulse Width
Pulse Shape
Pulse Energy

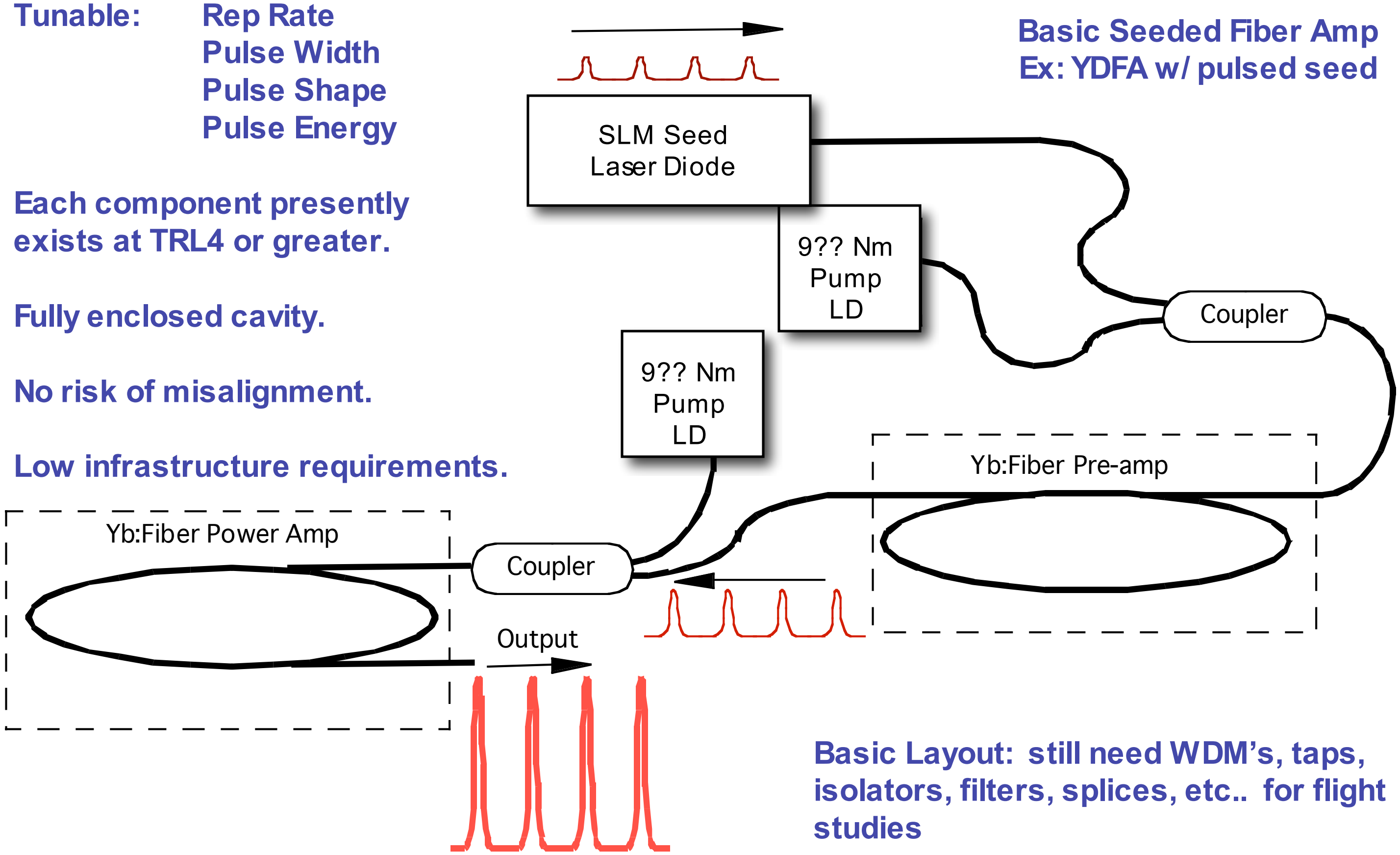
Each component presently exists at TRL4 or greater.

Fully enclosed cavity.

No risk of misalignment.

Low infrastructure requirements.

Basic Seeded Fiber Amp
Ex: YDFA w/ pulsed seed



Basic Layout: still need WDM's, taps, isolators, filters, splices, etc.. for flight studies

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Pulsed Fiber MOPA Technology:

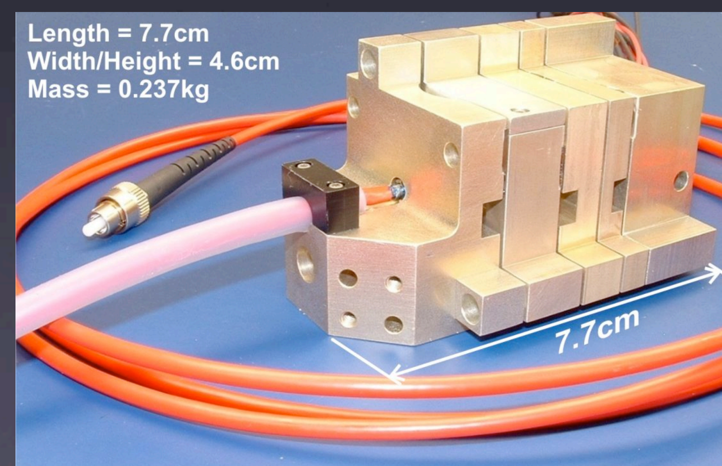
Candidate Components

JDSU 5 W pump module
TRL 5

1. At the component level, much of the required technology is actually flight competitive in its current form.
2. However, lots of packaging development and system level demonstration is needed ASAP.

OEM Yb:fiber amp
TRL 4-5

Prototype pulsed SLM 1064 nm seeder
TRL 4-5



Redesigned diode seeder for flight
TRL 5-6

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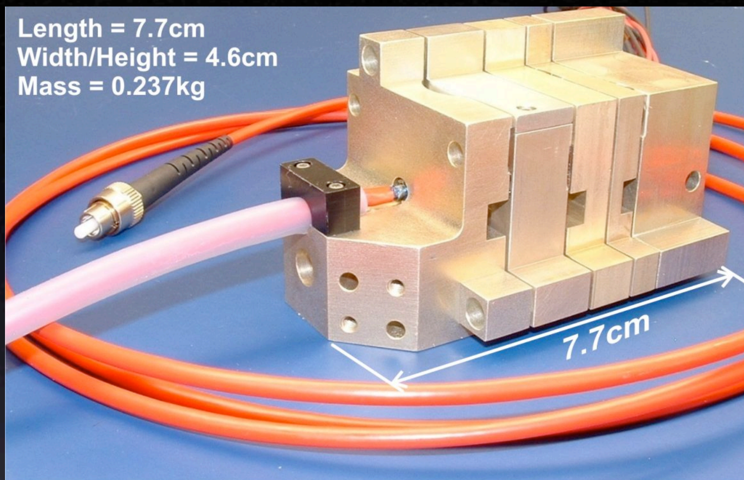
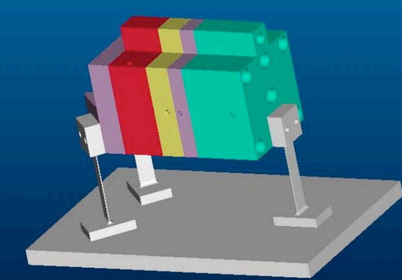
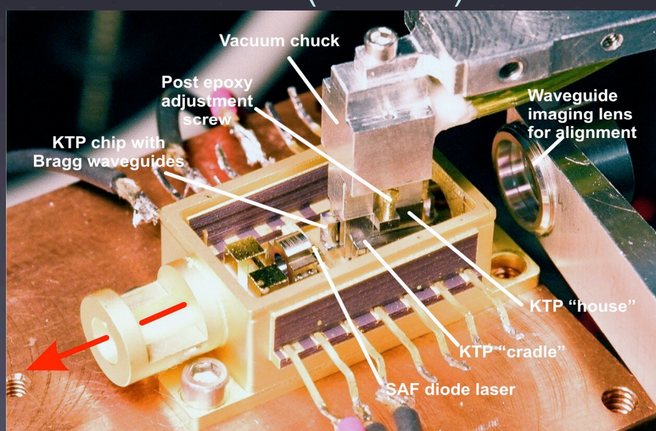
Pulsed Fiber MOPA Technology: Pulsed Seeder



2nd generation pulsed SLM 1 nm seeder
TRL 5-6 (10/2005)

2nd gen seeder FEA model for vibration test configuration





3rd generation pulsed SLM 1 nm seeder
TRL 5

Parameter	Specification
Linewidth cw	1MHz
Linewidth pulsed	40GHz at 5ns
Pulse width	3ns -100ns, adjustabled
PRF	cw – 100kHz, adjustable
Side mode suppression ratio (spectral purity)	≥ 40dB
Wavelength region	Factory set 1020 – 1080nm
Wavelength tunability	± 0.2nm using temperature
Frequency stability	< 100MHz hour
Output power	10mW cw
Output energy	2nJ pulsed at 5ns
Electrical consumption	1.5W during operation
Footprint	10 x 22 x 12mm
Output	SM fiber, 1µm

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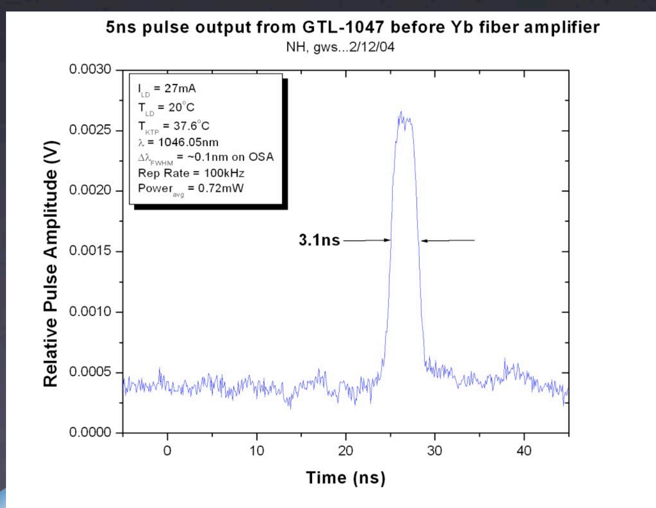
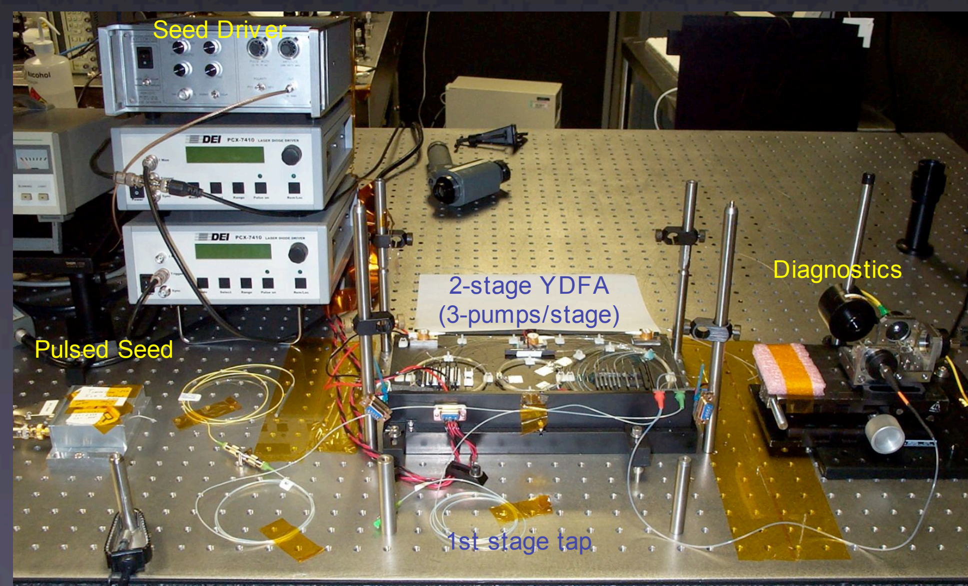
Seeded Pulsed Yb Fiber Amplifier for Real- Time Adaptable Altimetry and Imaging

Immediate variability of rep rates, pulse widths, and pulse energies can NOT be performed with cavity-based, solid state laser systems without each parameter effecting the others, including beam quality.

By using optimized pulse pumped, Yb:fiber amplifiers and discrete diode based seed @ 1064 nm or 1047 nm, the existing 1 um altimetry NASA infrastructure can readily incorporate a demonstration system into available aircraft instruments for evaluation and test.





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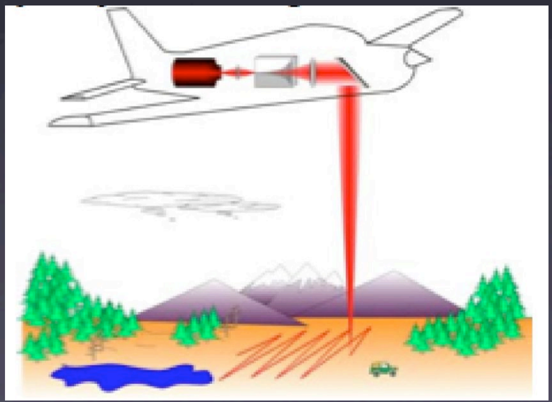
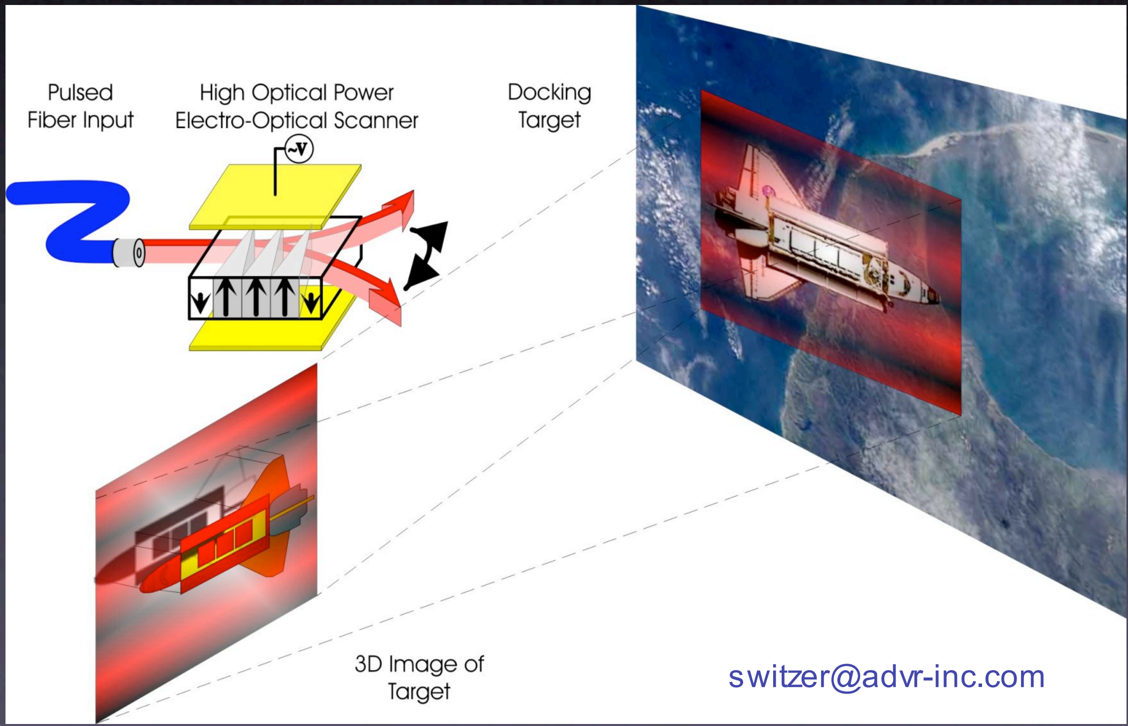
Fiber Transmitters Enable Use of New Technologies

Electro-optic beam deflector provides path for high density Scanning,imaging, and multi-plexed seeded fiber amps.





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Getting Fiber Amps to Space:

Near Term Efforts

- 1. Demonstrate in the lab and fully characterize performance for the most likely science mission. The goal here is to get it ready for an aircraft or non-lab environment.
- Try to identify the system's immediate sensitivities and weaknesses. Use peer review and/or objective critiques to correct these now if possible. (Very important!)
- Is it vibration sensitive? Probably somewhere, so start planning a 1st effort packaging study in order to understand this early in the process.
- Are all the components properly de-rated in their operation or use? Ex: Is there accurate data on the optical damage thresholds, diode duty factor and acceptable drive current.
- Monitor the performance over the lab studies and try to determine any slight degradations.
- Can the electronics and support equipment survive the dirty aircraft environment? Some board-level custom EE support may be needed.
- Can the system take large swings in humidity? Any exposed optics prior to final beam expansion must be kept clean. We will probably need a hermetically sealed box.
- In-flight adjustment may be required as diodes decay or radiation effects accumulate. Plan on leaving at least 1 major performance "knob" accessible outside the enclosure.
- Develop low-voltage electro-optic scanner technology for digitally controlled surface pattern production.

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Getting Fiber Amps to Space: Summary

- **Costs savings and infrastructure investments are very important factors often overlooked.**
- **Flight packaging fiber amplifier technology is often "down-played", or under-rated in difficulty. This could be a significant undertaking for a long life system.**
- **We are pursuing funding and seeded fiber amplifier development actively for the next generation of remote sensing instruments and greatly utilizing the industry.**

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