Advances on 2-micron Coherent Doppler Wind Lidar

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Acknowledgements: The authors appreciate the support of George J. Komar, NASA Earth Science Technology Office and Ramesh K. Kakar Science Mission Directorate at NASA HQ

Meeting of the US Working Group on Space-based Lidar Winds
May 13-14, 2014, Boulder, CO

Outline

- Background
- Roadmap
- Technology Development
  - 1.2 Joule/pulse energy demonstration
  - Compact 2-micron wind lidar transceiver
  - Conductive cooled 2-micron osc/amp development
- Ground and Airborne campaigns
- Fully Conductively-cooled Risk Reduction Laser
- Conclusions

Motivation for 2-Micron Laser/Lidar Development
NRC Recommended "3-D Winds" Mission

NRC Decadal Survey

EARTH SCIENCE AND APPLICATIONS FROM SPACE

NATIONAL IMPERATIVES FOR THE NEXT DECADE AND BEYOND

Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future

Space Studies Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES

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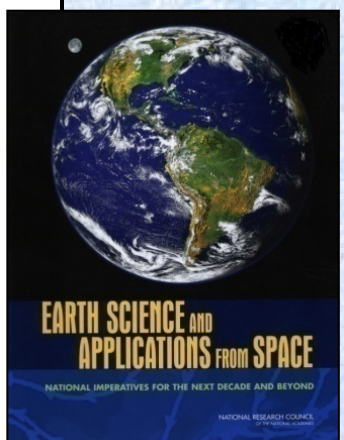
2007



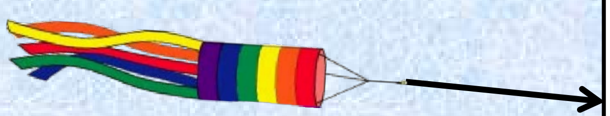
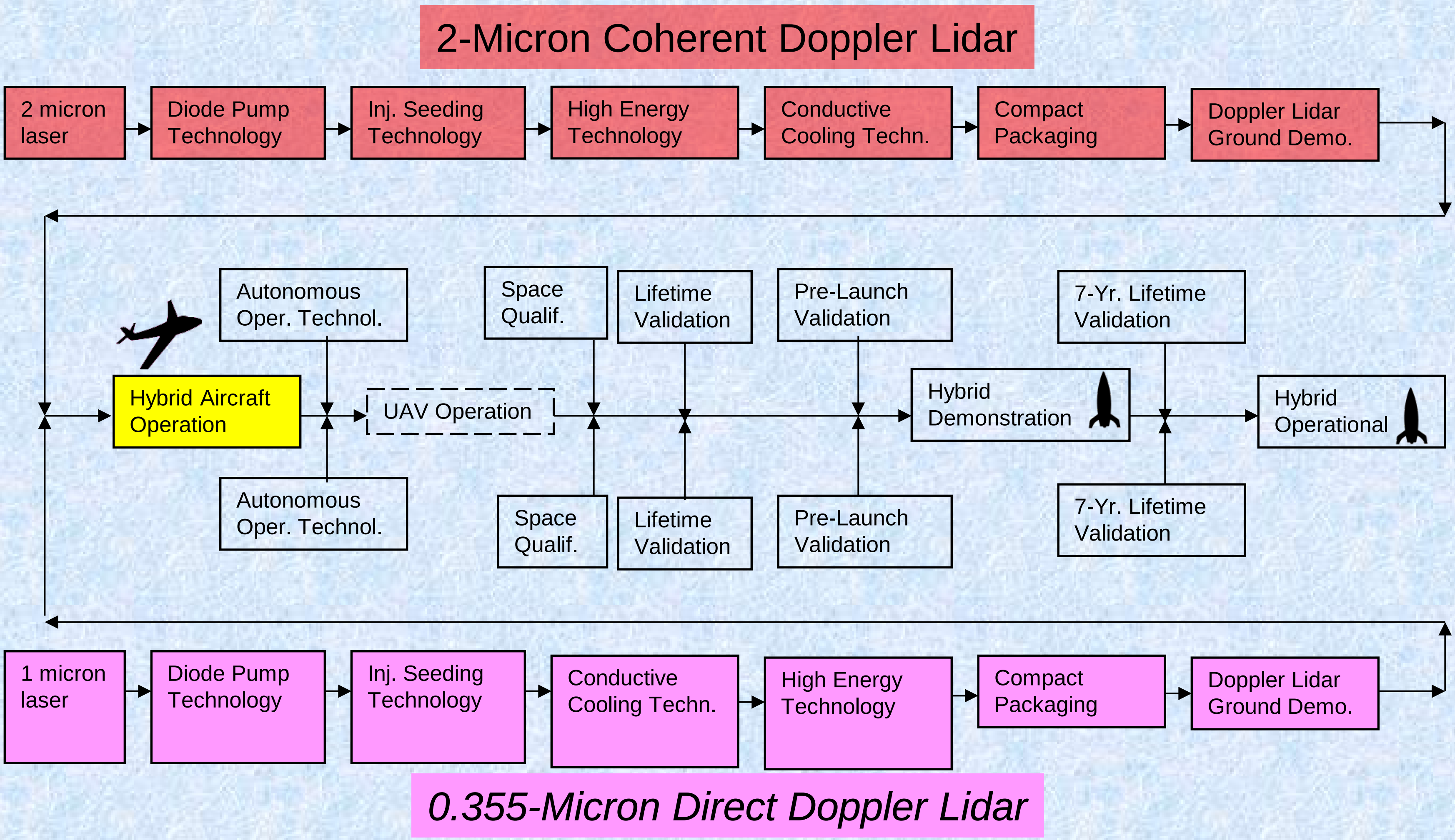


TABLE ES.2 Launch, Orbit, and Instrument Specifications for Missions Recommended to NASA

Decadal Survey Mission	Mission Description	Orbit[a]	Instruments	Rough Cost Estimate (FY 06 $million)
2010-2013				
CLARREO (NASA portion)	Solar and Earth radiation; spectrally resolved forcing and response of the climate system	LEO, Precessing	Absolute, spectrally resolved interferometer	200
SMAP				
ICESat-II				
DESDynI				
2013-2016				
HyspIRI				
ASCENDS				
SWOT				
GEO-CAPE				
ACE				
2016-2020				
LIST				
PATH				
GRACE-II				
SCLP	Snow accumulation for freshwater availability	LEO, SSO	Ku- and X-band radars K- and Ka-band radiometers	500
GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	LEO, SSO	UV spectrometer IR spectrometer Microwave limb sounder	600
3D-Winds (Demo)	Tropospheric winds for weather forecasting and pollution transport	LEO, SSO	Doppler lidar	650

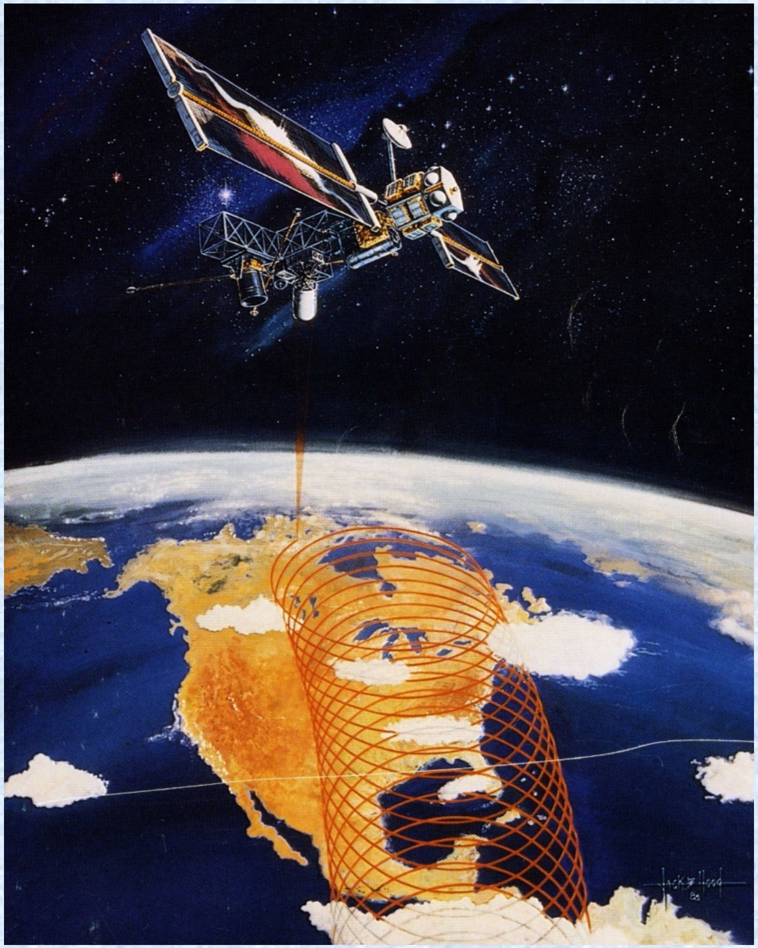
Global Winds 9 Societal Benefits	
Extreme Weather Warnings	✓
Human Health	✓
Earthquake Early Warning	
Improved Weather Prediction	**✓#1**
Sea-Level Rise	
Climate Prediction	
Freshwater Availability	
Ecosystem Services	
Air Quality	✓

Space-Based Doppler Wind Lidar Roadmap



Global Winds Roadmap Via Hybrid Doppler Lidar

Early Mission Concept for Earth Winds Laser Atmospheric Wind Sounder (LAWS)



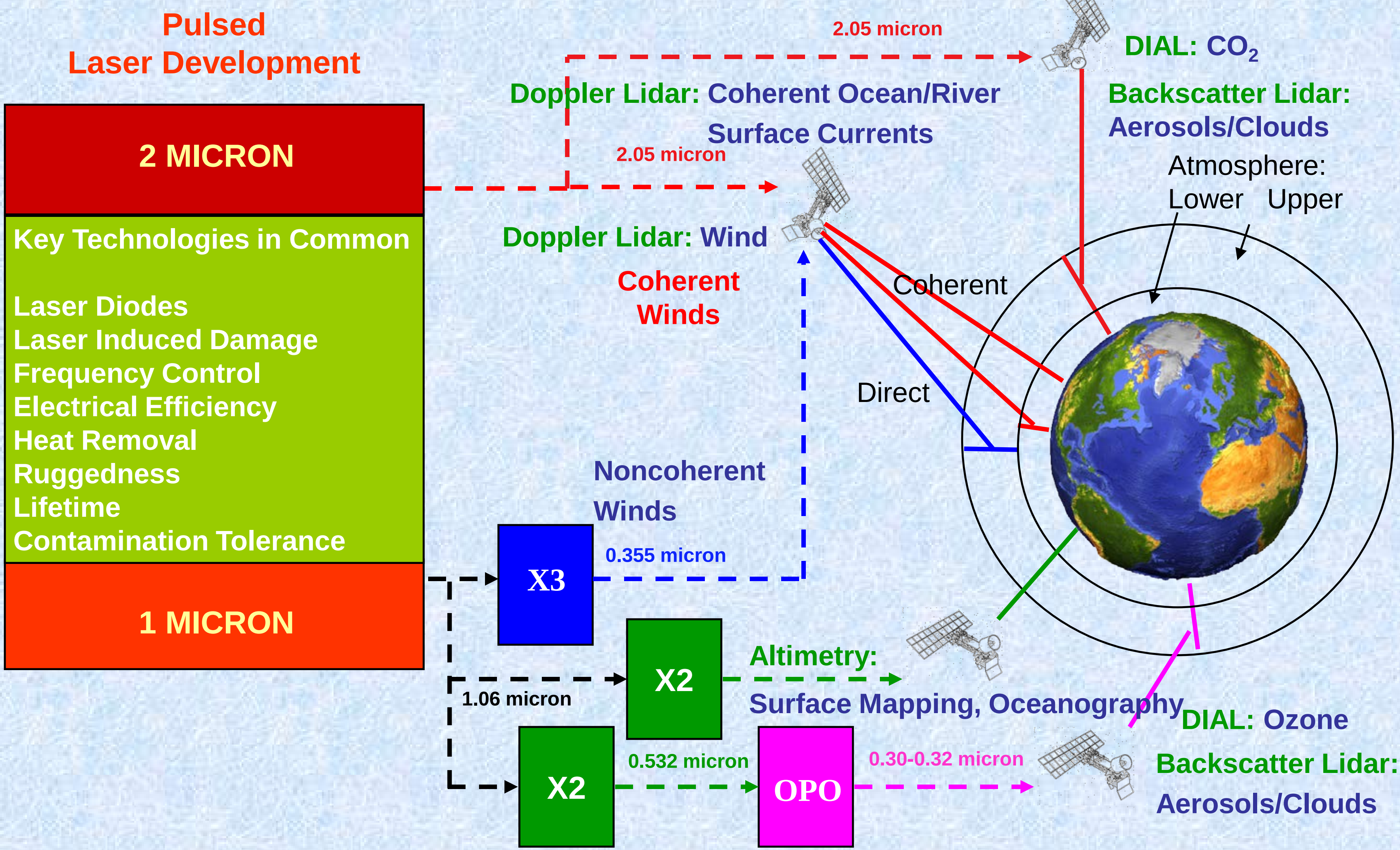
- 525 km orbit height
- Single pulsed coherent Doppler lidar system covers troposphere
- Continuously rotating telescope/scanner
- Line of sight (LOS) wind profiles from each laser shot
- ~ 20 J pulse energy
- ~ 1.5 m rotating telescope

- Requirement: eyesafe solid state pulsed laser
- 2-micron technology for coherent detection
- 20 mJ/5 Hz demonstrated vs. 20 J/10 Hz req.
- Energy deficiency of x1000 (30 dB) !

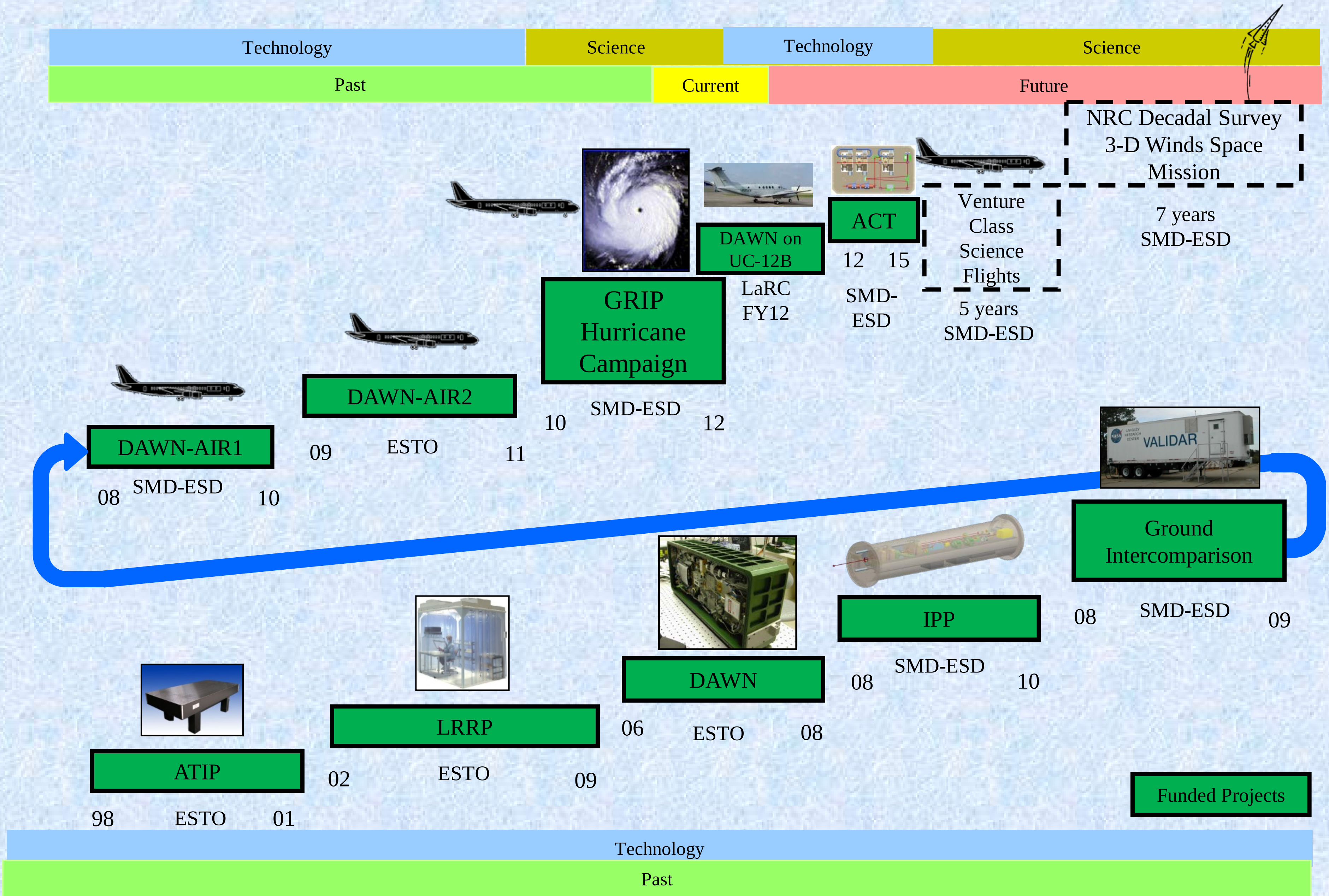
Laser Risk Reduction Program (LaRC-GSFC)

(NASA HQ Funded Directed Program 2001-2010)

2 Lasers, 4 Techniques, 6 Priority Measurements



Roadmap to 3-D Winds Space Mission at NASA Langley



Objectives & Technical Approach

Objectives

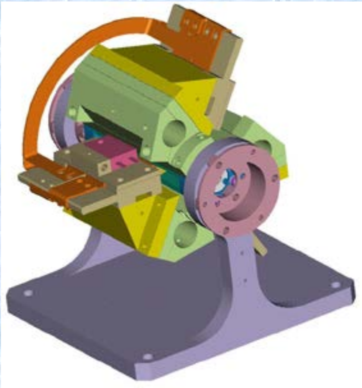
Develop related laser technologies leading to a conductively cooled, diode-pumped high-energy and high-efficiency 2-micron pulsed laser suitable for space-based remote sensing Lidar applications to support science and exploration missions.

Technical Approach

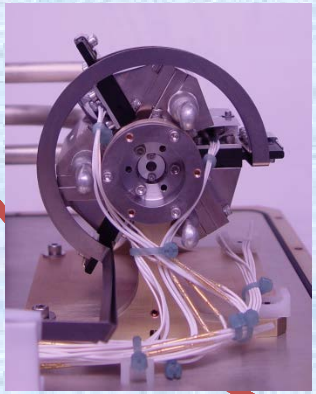
"Systematically conduct theoretical and experimental research to develop related laser technologies included but not limited to new laser materials, innovative cavity designs, pump module designs, diode configurations, advanced thermal management systems, creative mechanical design and fabrication technologies."

Technology Maturation Example

A fully conductively cooled 2-micron solid-state pulsed laser has been demonstrated to enable 3-D Winds from a space platform



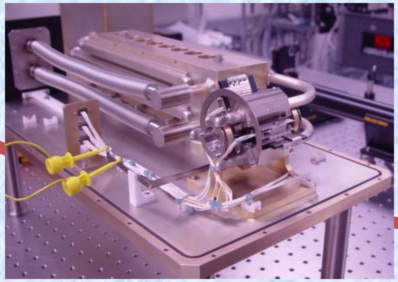
Analysis & Design



Fabrication

Space Qualifiable Design

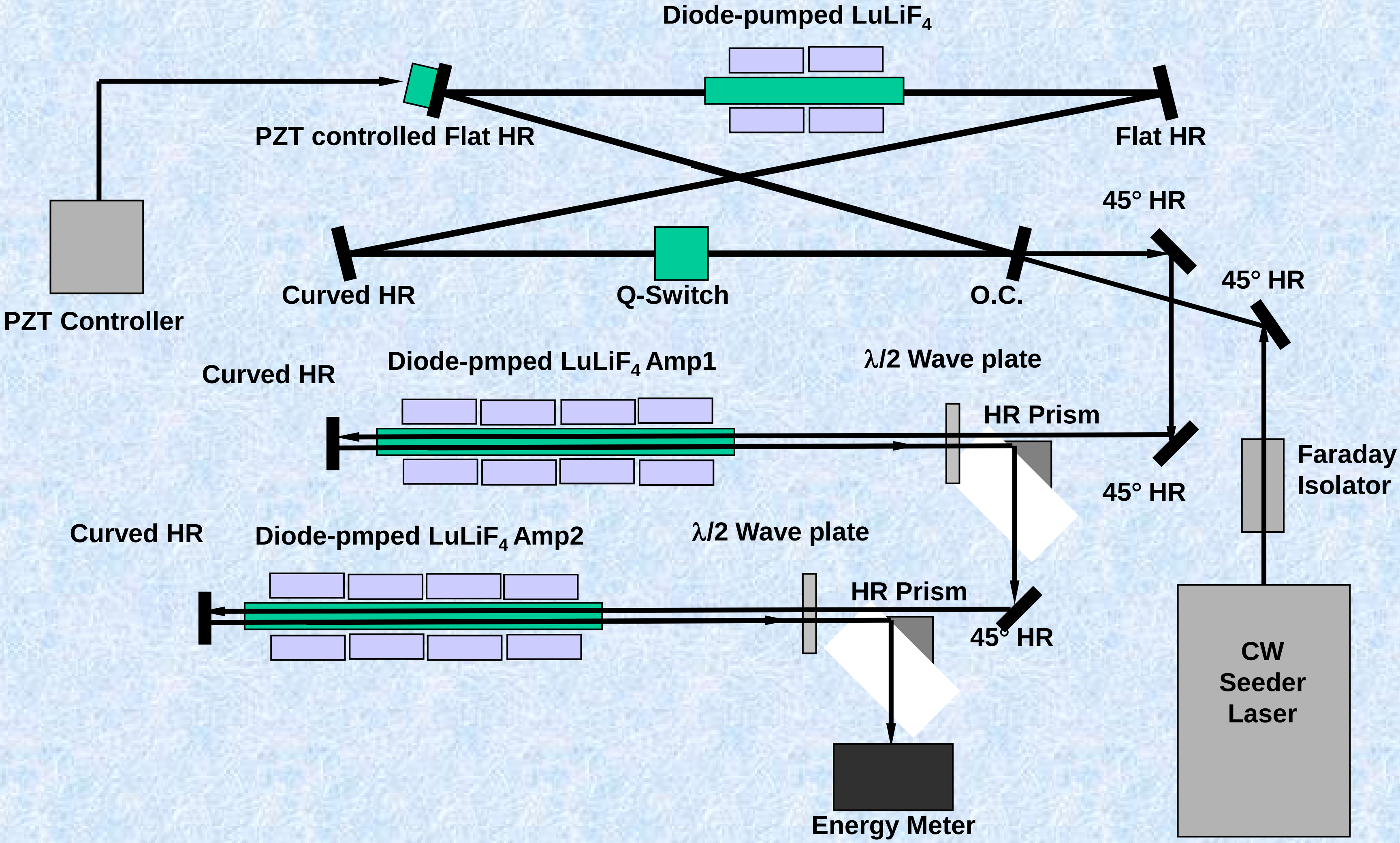
Quantum Mechanical Modeling



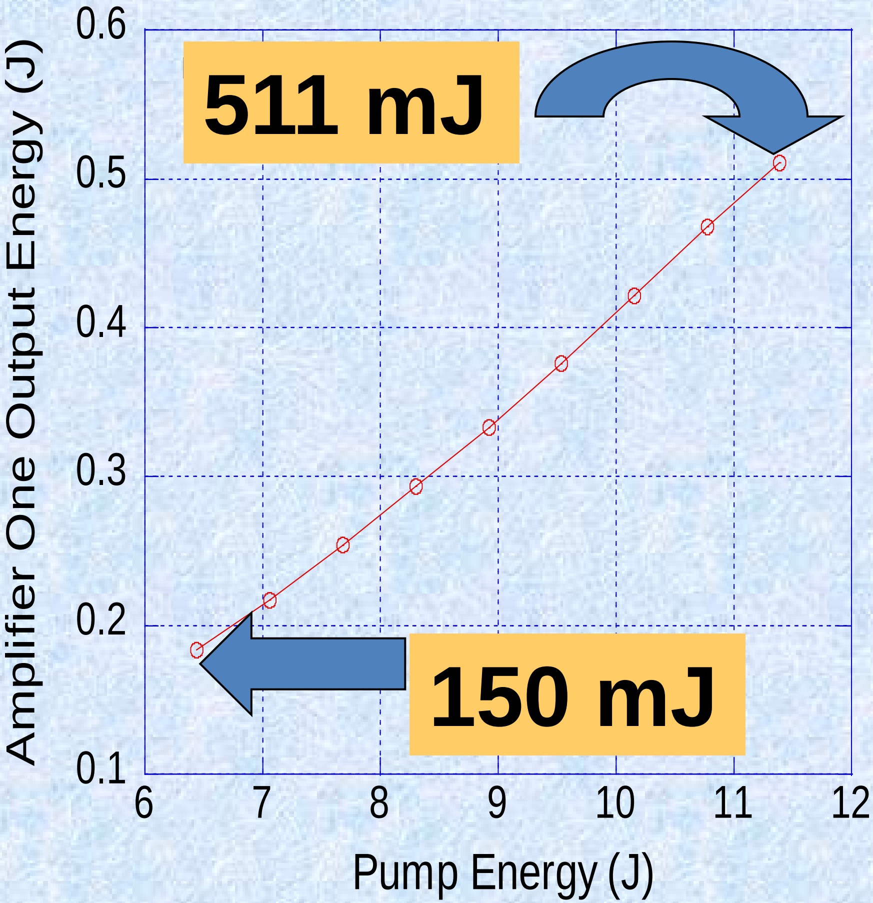
System Integration

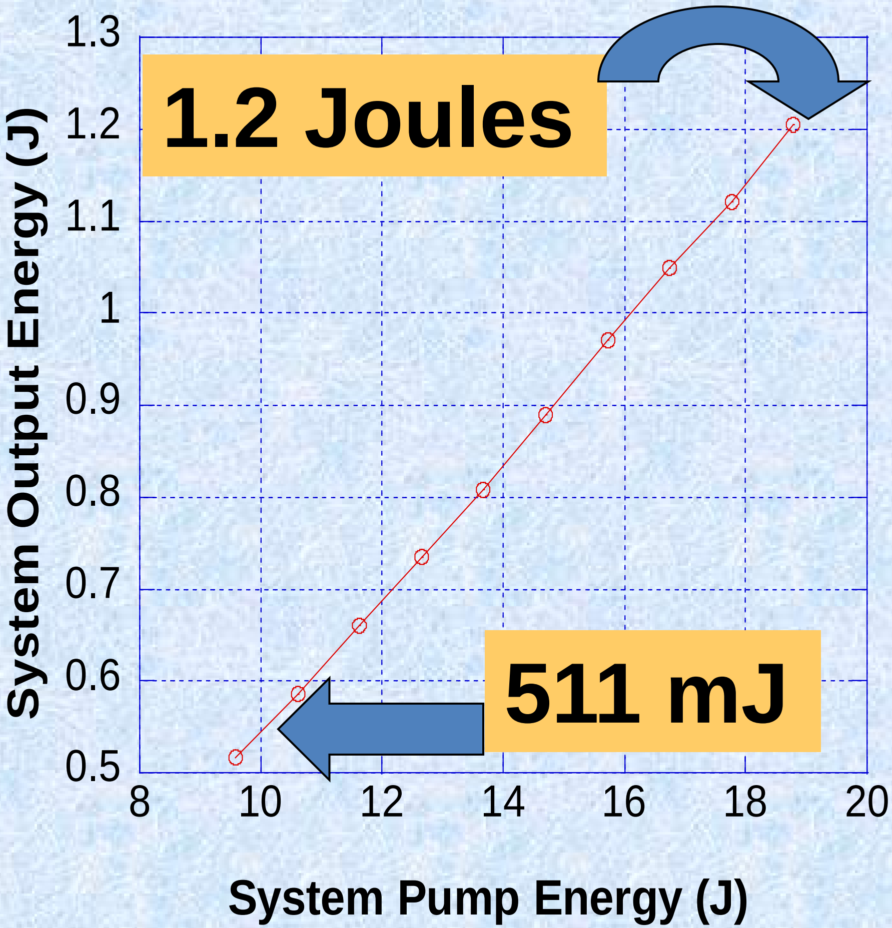
Testing and Model Verification

MOPA Schematic



Amplifier Performance
(First and Second)



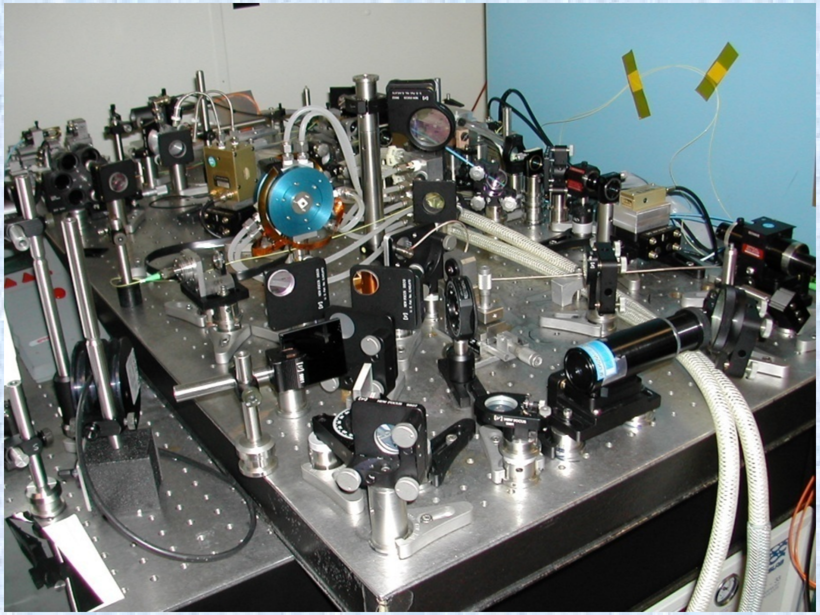


Mobile Ground based High Energy Wind Lidar Transceiver – LRRP/DAWN Funded

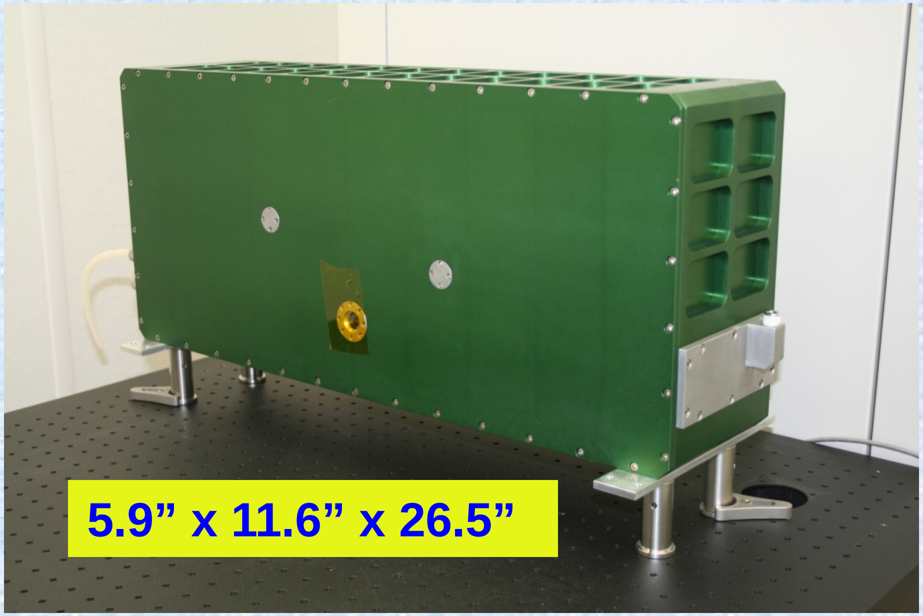
Table Top Transceiver (Transmitter + Receiver)
90 mJ/pulse, 5 pulses/sec.
3'x4' Optical Table
(no telescope or scanner)

- **Smaller**
- **More energy**
- **More robust**

Transceiver (Transmitter + Receiver)
250 mJ/pulse, 10 pulses/sec.
5.9" x 11.6" x 26.5", 75 lbs.; 15 x 29 x 67 cm, 34 kg
(no telescope or scanner)



Previous implementation
90 mJ per pulse



Small, Robust, 250 mJ per pulse

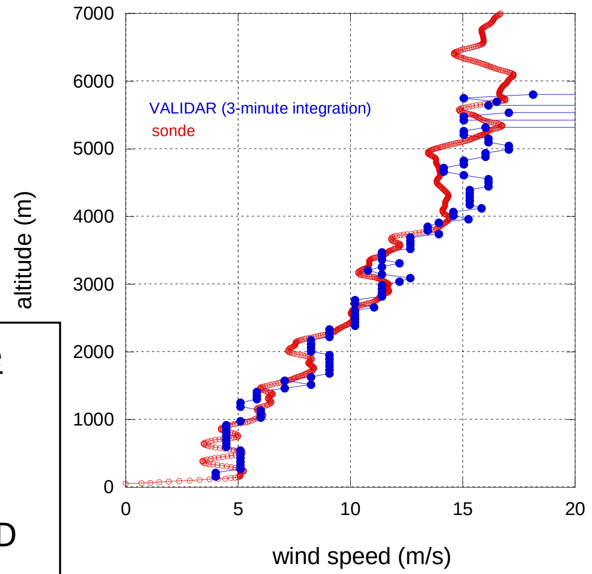
2-μm Lidar Parameters

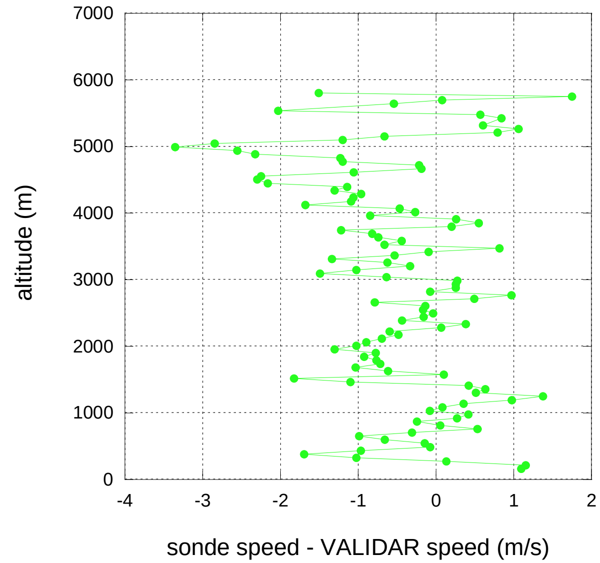
- Pulse energy = 250 mJ
- Pulse repetition rate = 5 Hz (currently at 10 Hz)
- Pulsewidth = 200 ns
- Telescope aperture = 15 cm
- Wavelength = 2053 nm (Ho:Tm:LuLiF)
- Data acquisition : 500 Ms/s, 8 bits, real-time processing
- Scan pattern: zenith view interleaved with 45-degree elevation cone
- Operations: run continuously up to 84 hours, unattended for long periods

Ground-Based Hybrid Wind Lidar Demo
Winter 2009

- The LaRC mobile lidar is deployed as part of NASA HQ funded (ROSES-2007, Wind Lidar Science Proposal entitled "Intercomparison of Multiple Lidars for Wind Measurements (PI: Upendra Singh)
- Utilized NASA LaRC Compact DAWN Lidar Transceiver for 2-micron lidar
- Site at Howard University Research Campus in Beltsville, Maryland

Comparison of Coherent Lidar and Sonde

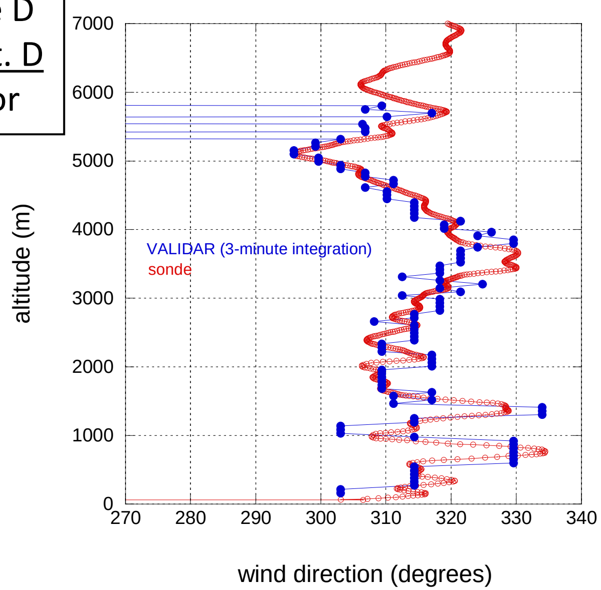


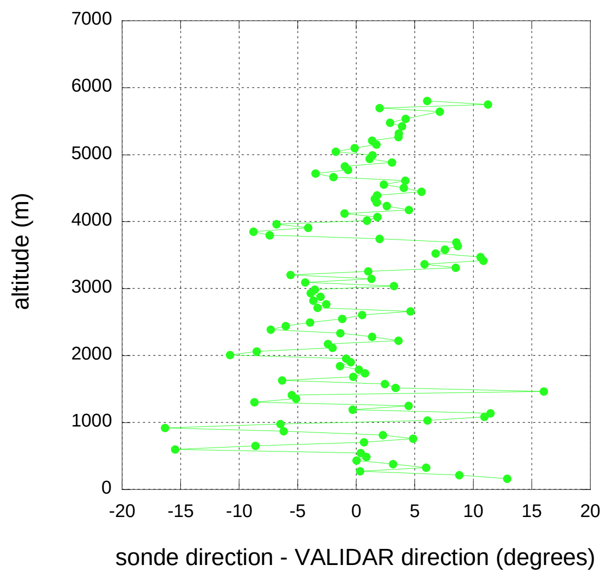


- Root-mean-square of difference between two sensors for all points shown = **<u>1.06 m/s</u>**

<u>Error Tree</u>

Lidar
+Sonde
+Location D
+Time D
+M Volume D
<u>+M Time Int. D</u>
=Total Error





- Root-mean-square of difference between two sensors for all points shown = **<u>5.78 deg</u>**

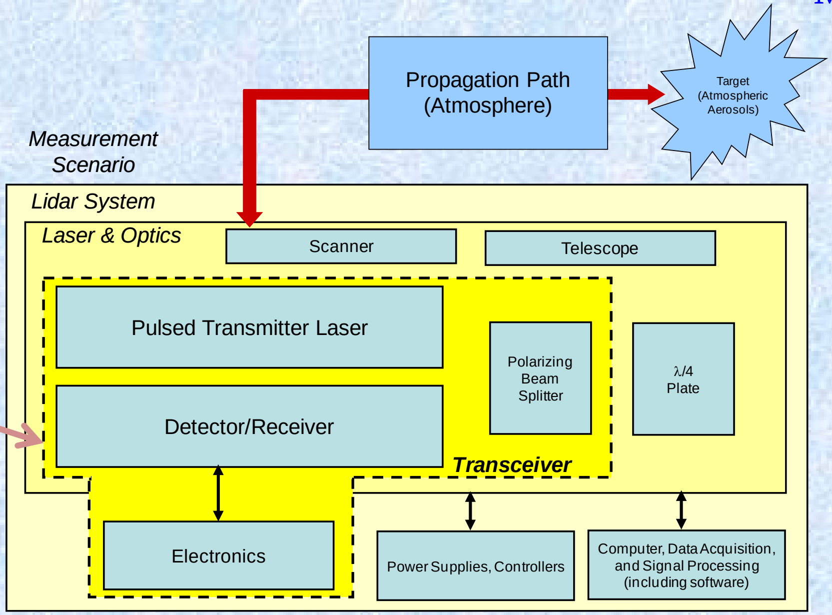
Genesis and Rapid Intensification Process (GRIP) Campaign

Coherent Pulsed Doppler Wind Profiling Lidar System

1. World's Most Capable Transceiver
Packaged, Compact, Robust

- 0.25 J pulse energy, 10 Hz pulse repetition frequency (PRF)
- 15 cm receiver optical diameter, 34 kg (75 lbs.)
- 15.2 x 29.5 x 67.3 cm (6 x 11.6 x 26.5 inches)

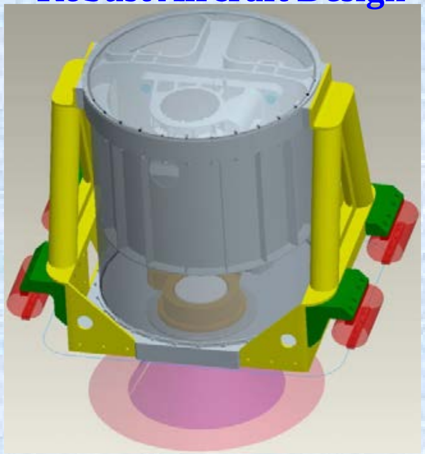
2. Complete System Utilizing Transceiver



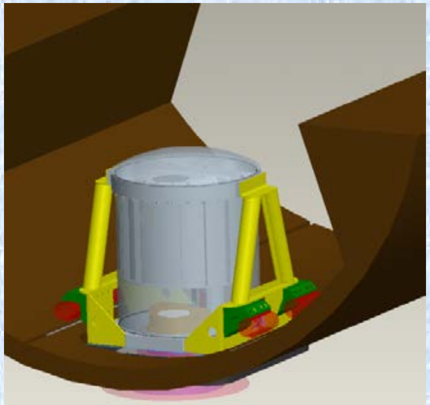
3. Ground-based Wind Measurement Performance

- RMS wind difference from balloon sonde, 0 – 6 km altitude, = 1.1 m/s and 5.8°
- No alignment needed after interstate travel in trailer
- Overnight unattended operation
- Vertical winds to 11 km altitude
- Horizontal vector winds to 7 km altitude
- Data processing choice of multiple values of vertical and horizontal resolution
- Same technology as anticipated space mission

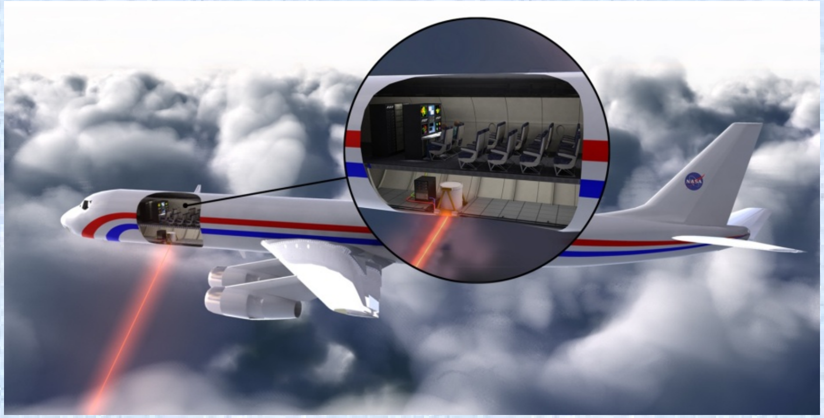
4. Enclosure for All Lidar Optics
Robust Aircraft Design



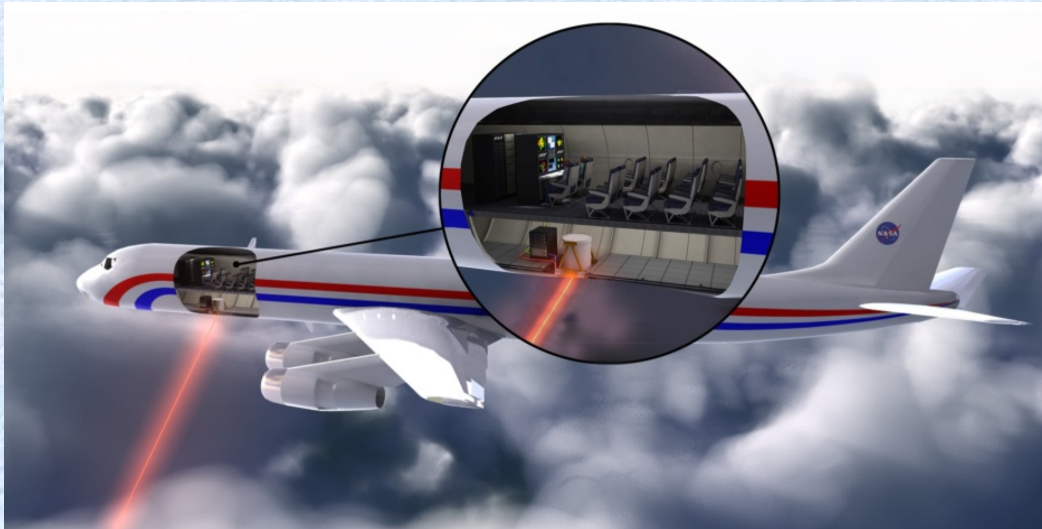
5. Optics in DC-8

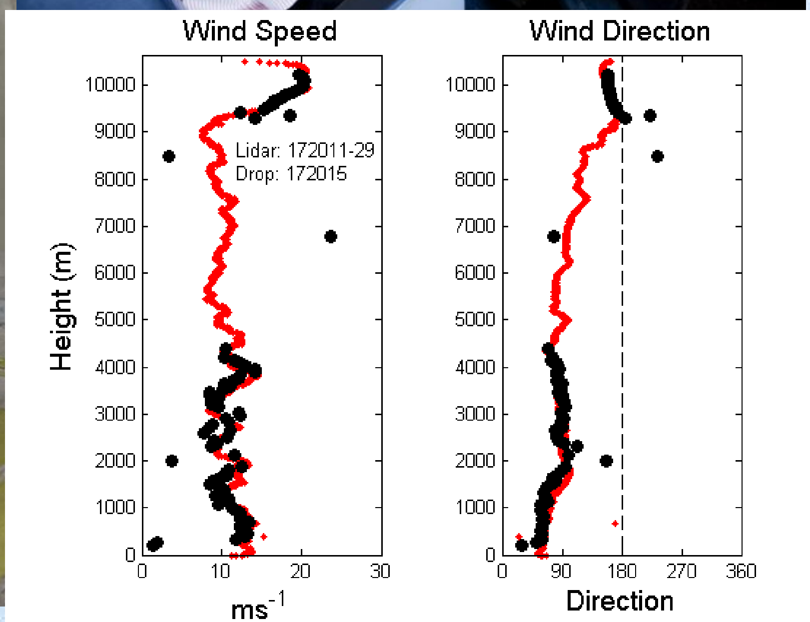


6. Lidar System in DC-8



NASA Langley DC-8 Wind Lidar During GRIP (2010)





Ho:Tm:LuLiF, 2.05 micron, 250 mJ, 10 Hz, 15 cm, coherent-detection

Langley Research Center

Toward 3D-Winds

(NASA ESTO investments)

Tropospheric Wind Lidar Technology Experiment (TWiLiTE)

UV Direct Detection Molecular Winds
(Gentry, NASA GSFC)

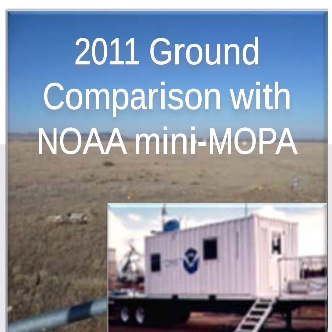
Doppler Aerosol Wind Lidar (DAWN)

2.0 um Coherent Doppler Aerosol Winds
(Kavaya, NASA LaRC)

Optical Autocovariance Wind Lidar (OAWL)

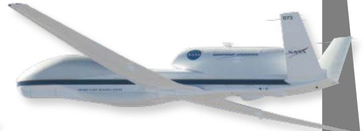
UV Direct Detection Aerosol & Molecular Winds
(Grund/Tucker, Ball Aerospace)

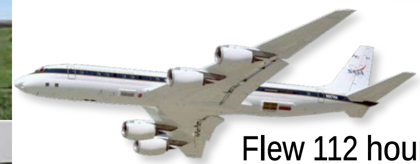
2008 Ground Comparison
(Singh, NASA LaRC)

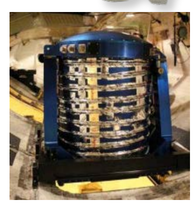


2011 Ground Comparison with NOAA mini-MOPA

Flew on the ER-2 in 2009 & 2011 and is being configured to fly on the Global Hawk for the Hurricane and Severe Storm Sentinel (HS3) EV-1 Mission in 2012.





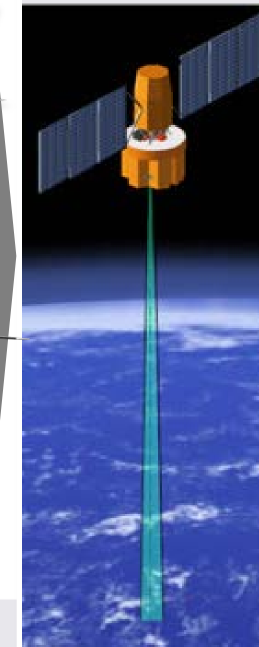


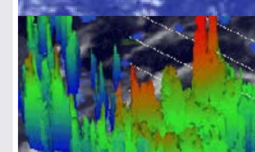
Flew 112 hours over 15 flights on the DC-8 in 2010 in support of the NASA GRIP campaign. Additional flights are planned on the B200.

Test flights conducted on the WB-57 in 2011.

IDL / MDL testing, and an Observing System Simulation Experiment (*OSSE*) are planned for 2012.

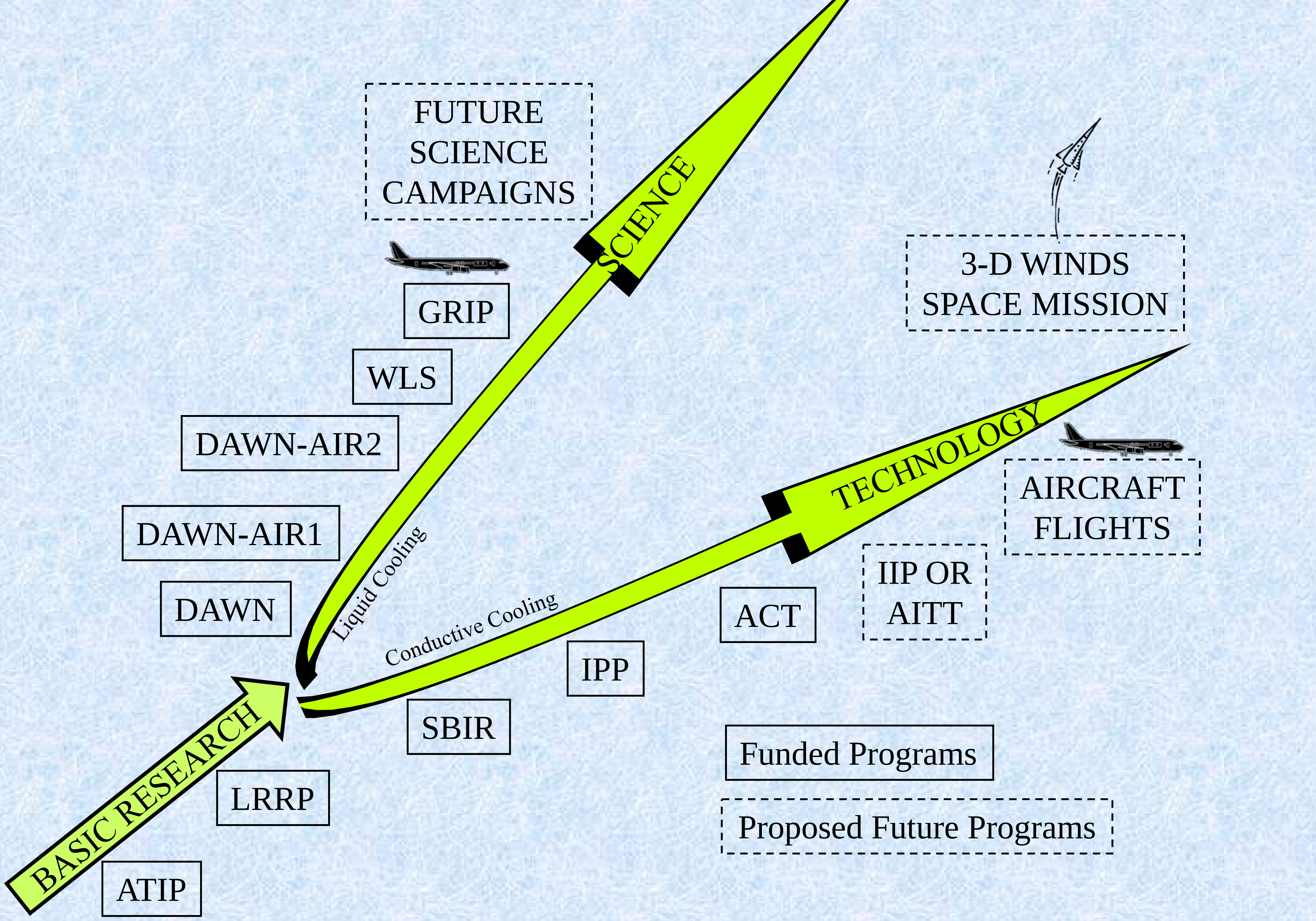
3D-Winds Decadal Survey Mission





Technology Development → **Demonstrations / Campaigns** → **Science Measurements**

3-D Winds Mission Science and Technology Roadmap



LaRC Partnership with Fibertek for Space Qualifiable 2-micron Laser Development for NASA 3-D Wind Mission

- **Laser Risk Reduction Program (ESTO) - 2001-’10**
  - LaRC has demonstrated fully conductively cooled oscillator/amplifier to 400 mJ, 5 Hz (08/07)

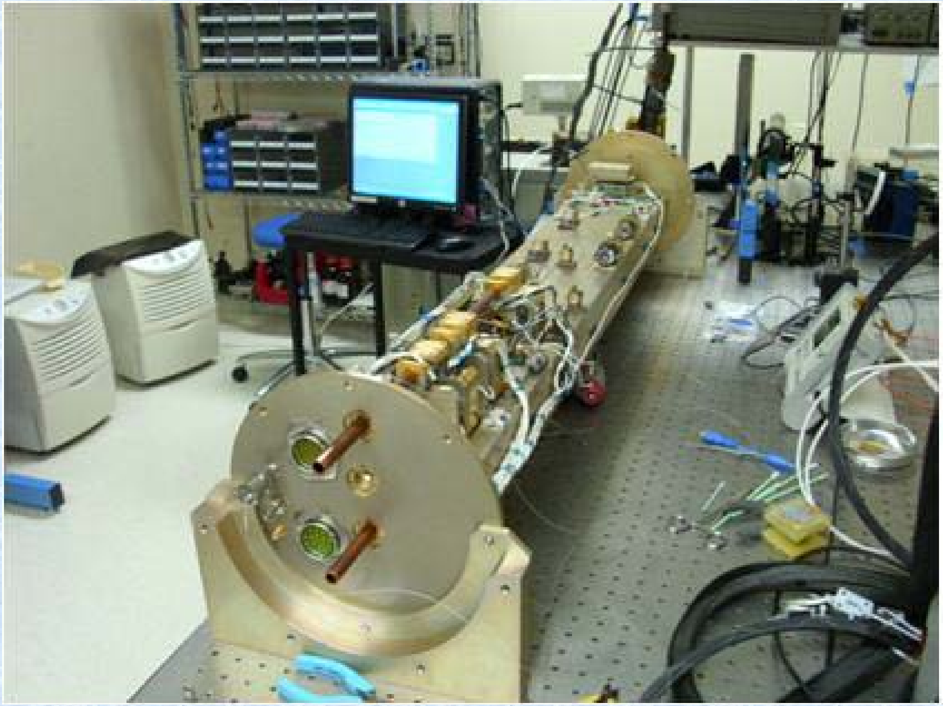
Partnership with Fibertek:

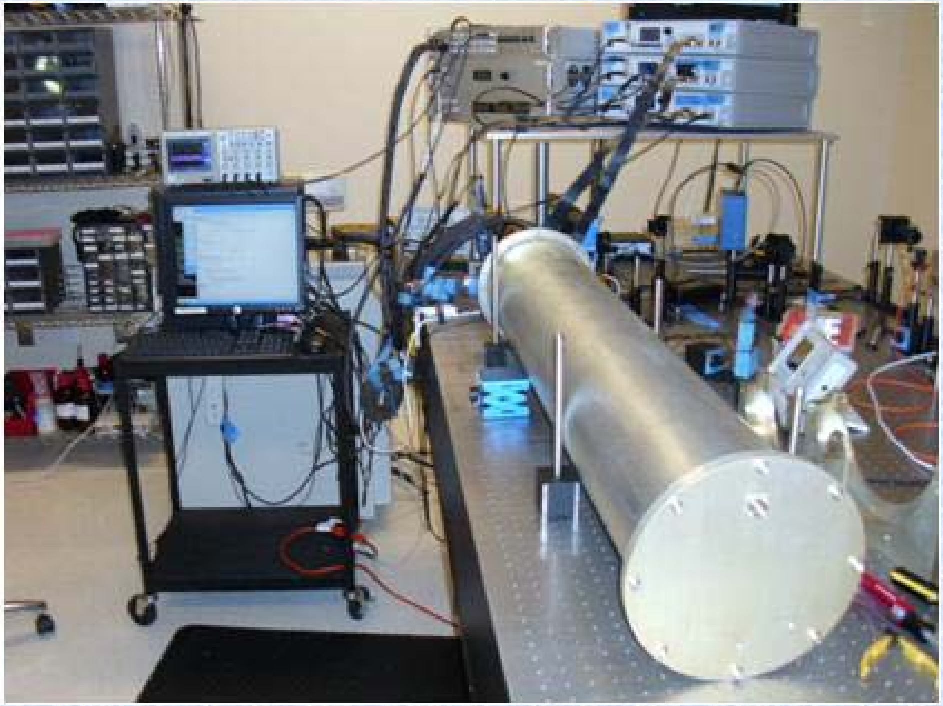
- **Innovative Partnership Program (LRRP/ESD/Fibertek)**
  - 3-m cavity, 792 nm pumped, conductively cooled 200 mJ, single frequency output at 5 Hz – first generation
- **Advanced Component Technology (LaRC/ESTO/Fibertek)**
  - Compact, 1-meter cavity, 808 nm pumped, fully conductively cooled laser transmitter delivering wind quality 250 mJ 10 Hz output for 3-D Wind mission

Innovative Partnership Program (LRRP/ESD/Fibertek) 2007-2010

(PI: Singh, Co-I: Yu, Kavaya LaRC; Co-I: Hovis, Fibertek)

Single frequency 2-micron Laser (200 mJ/5Hz) built and delivered by Fibertek to NASA LaRC





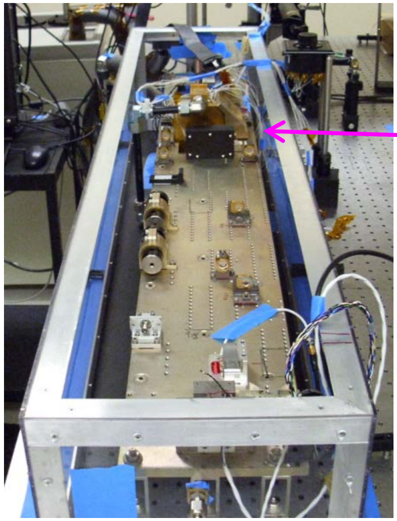
2-micron Risk Reduction Laser Transmitter

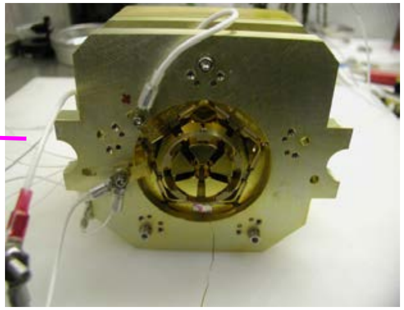
Design and Fabrication of a Breadboard, Fully Conductively Cooled, 2-Micron, Pulsed Laser for the 3-D Winds Decadal Survey Mission

PI: Upendra Singh, NASA LaRC

Objective

- Design and fabricate a space-qualifiable, fully conductively-cooled, 2-micron pulsed laser breadboard meeting the projected 3-D Winds mission requirements
    - Utilize improvements in key technologies including high-power, long-life space-proven 804 nm pump diodes; derated diode operation, and heat pipe conductive cooling
- Perform a long-duration life test on the laser system to evaluate mission readiness.





2-Micron Space Qualifiable Pulsed Laser for 3-D Winds
Left: early breadboard,
Above: ruggedized laser head

Approach

- Leverage LaRC 2-micron laser development from earlier efforts
- Utilize Fibertek CALIPSO mission flight laser design and development knowledge
- Upgrade previous Fibertek two-micron laser design for flight-like laser based on space heritage
- Utilize space-ready, sealed cylindrical package
- Perform vacuum and lifetime tests while operating at the output requirements of the 3-D Winds mission

Key Milestones

• Complete laser mechanical design update and improved laser thermal modeling	01/13
• Assemble and test heat pipe cooled module	04/13
• Fabricate and test ring laser with heat pipe cooled module	12/13
• Install and test amplifiers	03/14
• Integrate with canister and test	04/14
• Vacuum-test laser	10/14
• Complete 8 months of life testing	03/15
• Complete analysis and performance testing	04/15

Co-Is/Partners: Jirong Yu, Michael Kavaya, LaRC; Floyd Hovis, Tim Shuman, Fibertek, Inc.

TRL_{in} = 3 $TRL_{current}$ = 3

04/12

Earth Science Technology Office

Objectives of ACT

- Advance the technical maturity of a solid state 2 µm laser to TRL-5
- Fabricate a ruggedized, conductively-cooled, high energy solid state 2 µm laser transmitter meeting the performance requirements of an airborne or space-borne coherent detection or hybrid wind LIDAR system
- A thermal vacuum test will be used to demonstrate achievement of TRL-5

Basic Performance Goals

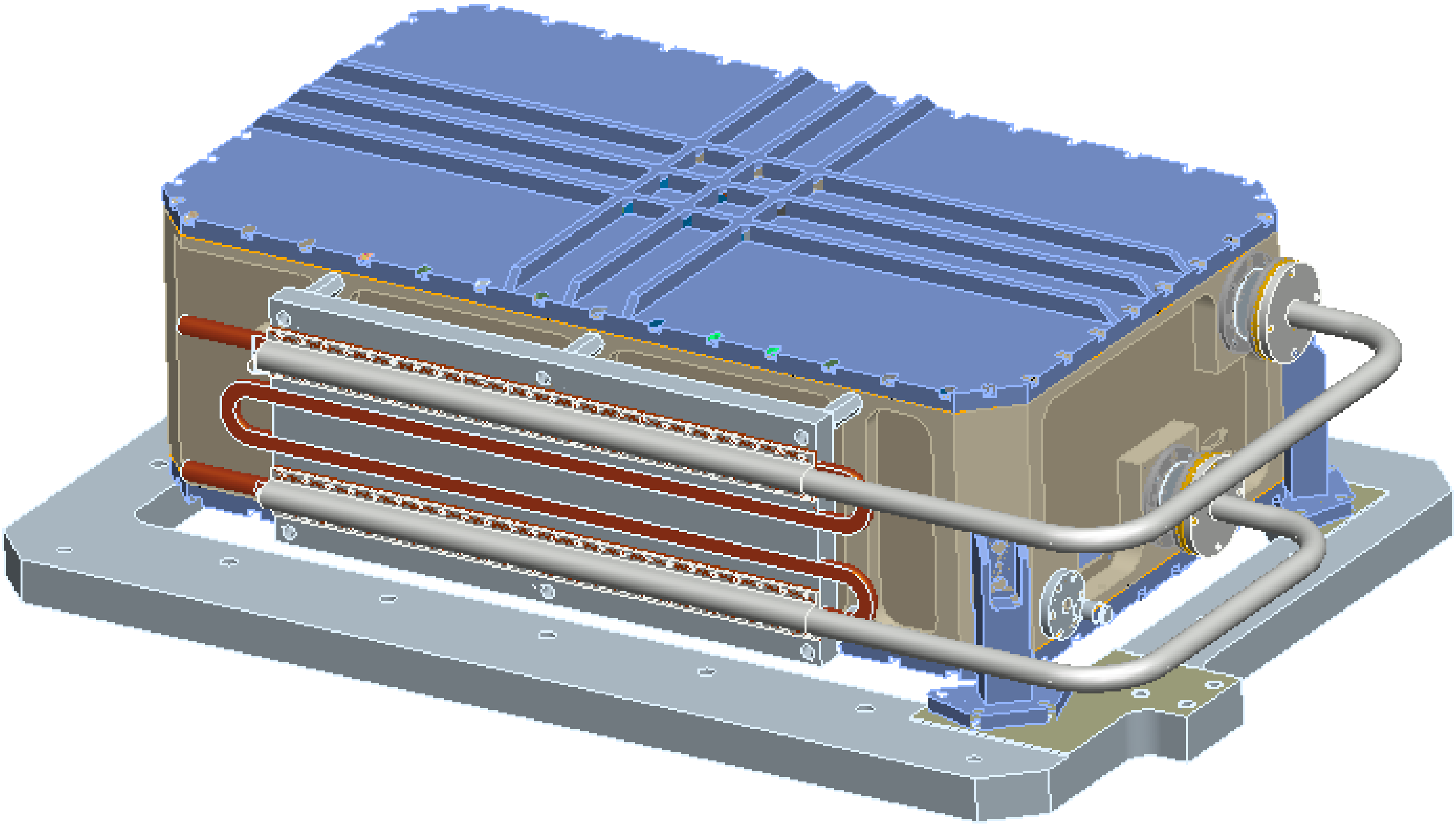
Wavelength	2.053 microns
Laser Pulse Energy	250 mJ
Repetition Rate	10 Hz
Pulse Width	>100 ns
Beam Quality	M^2< 1.2
Pulse Spectrum	Single frequency (seeded)
Cooling	Conductively cooled via heat pipes
Laser Head Size	23.9” x 14” x 7.7” (L x W x H) Including heat pipes and condenser

Langley Research Center

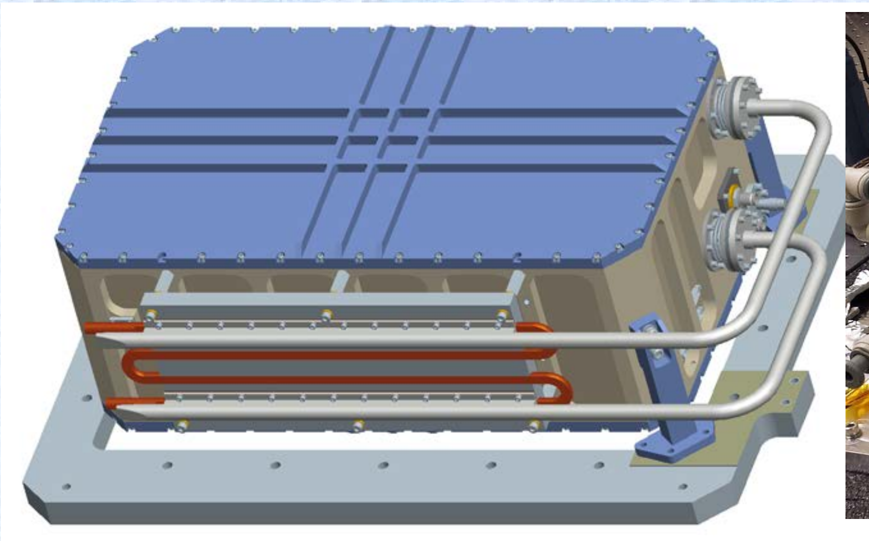
Conductively Cooled 2 μm Laser in Expanded ICESat-2 Housing

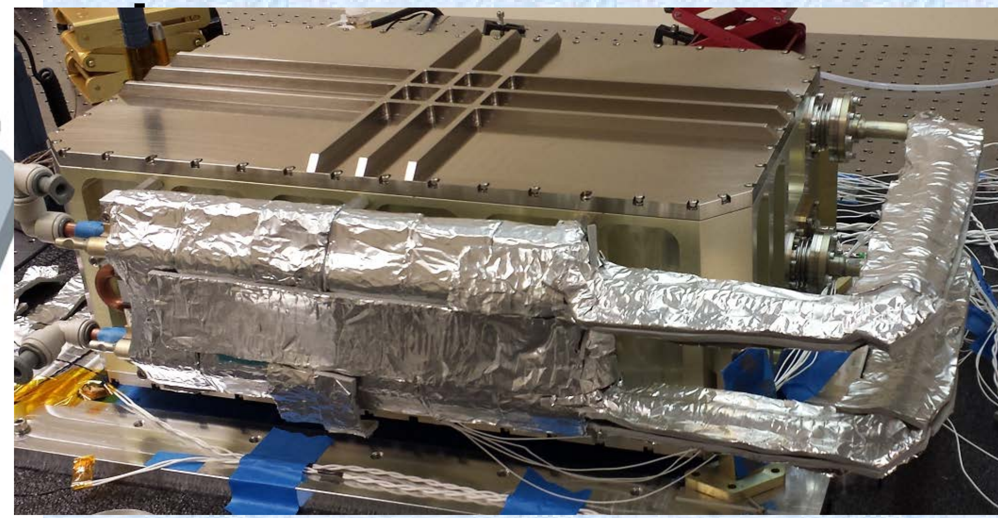
Box dims: 19"x11"x7.1" (LxWxH)
ICESat-2: 16"x11"x4.4" (LxWxH)
Mounting feet for illustration only

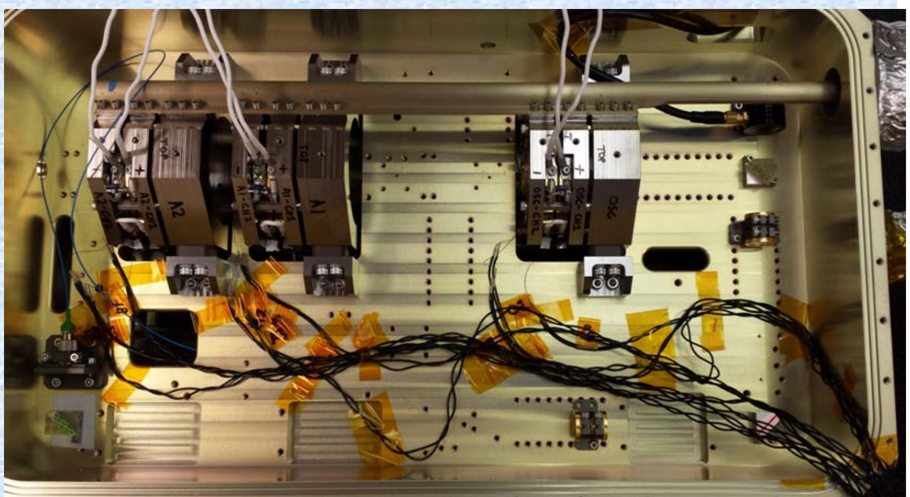
Housing itself: 19"L x 11"W x 6.1"H
Complete assembly : 23.9"L x 14"W x 7.7"H

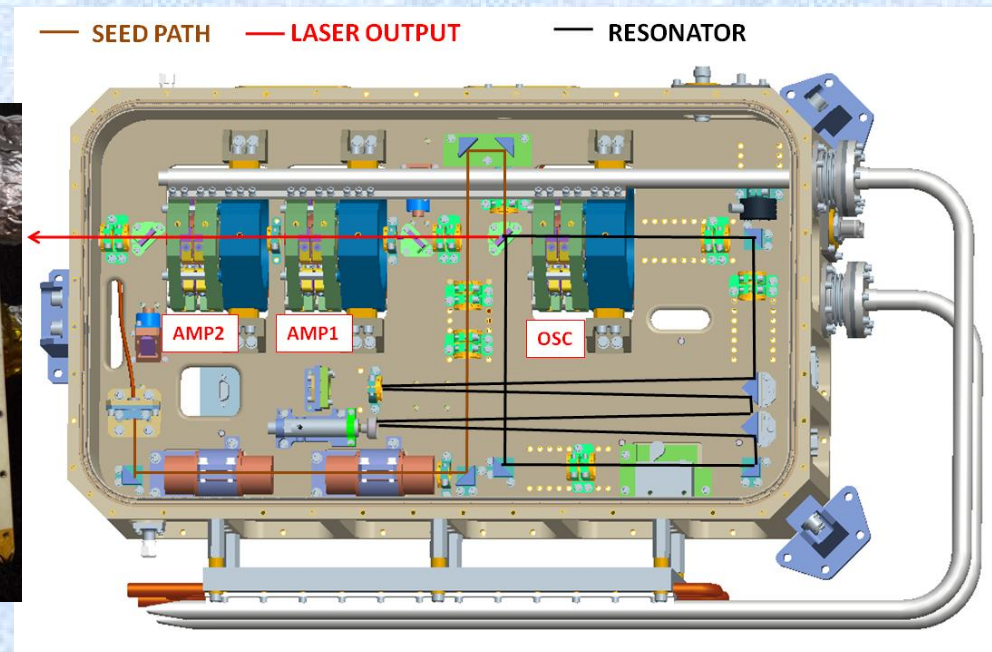


Conductively Cooled Laser

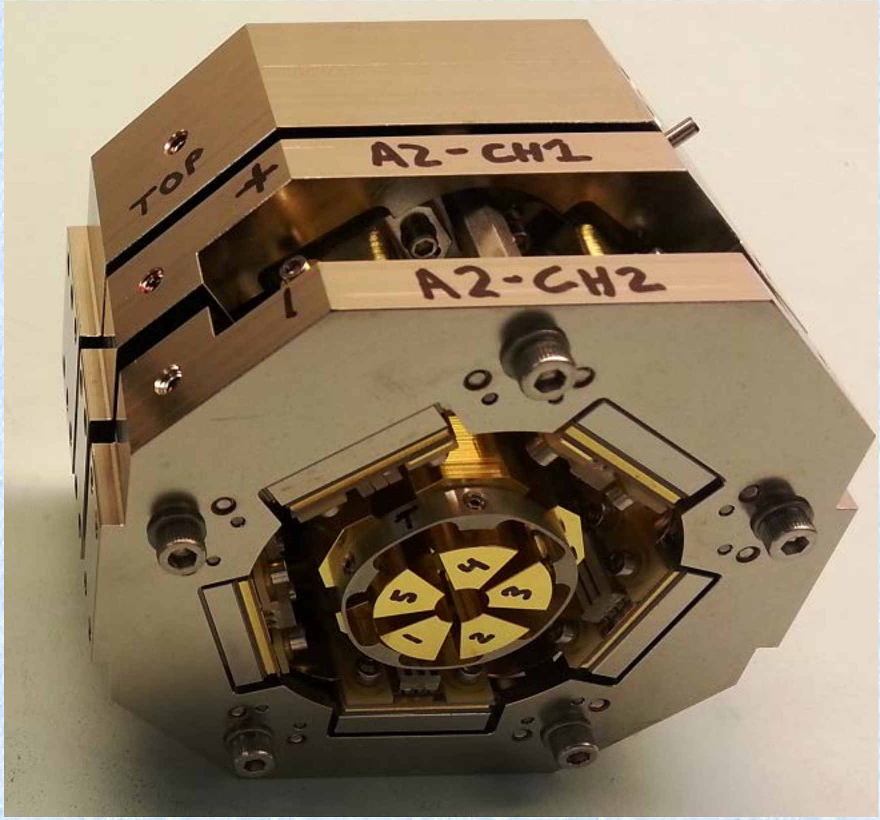






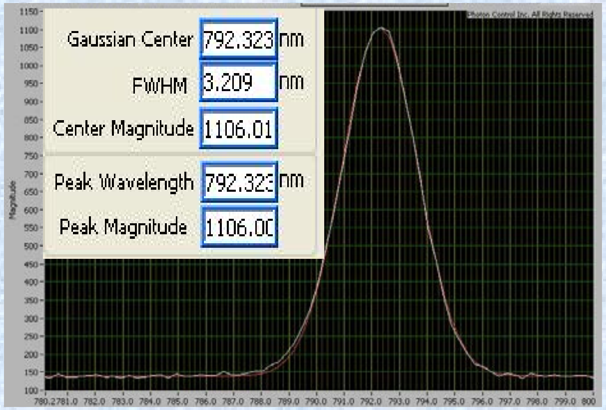


Pump Module Design & Hardware

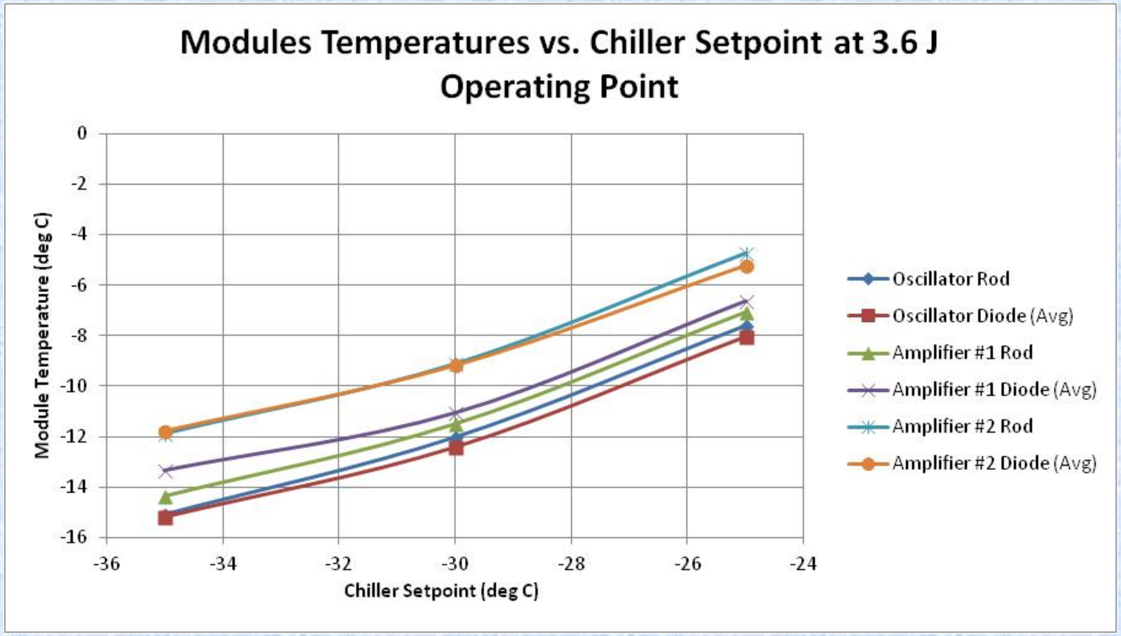


Thermal Management Performance

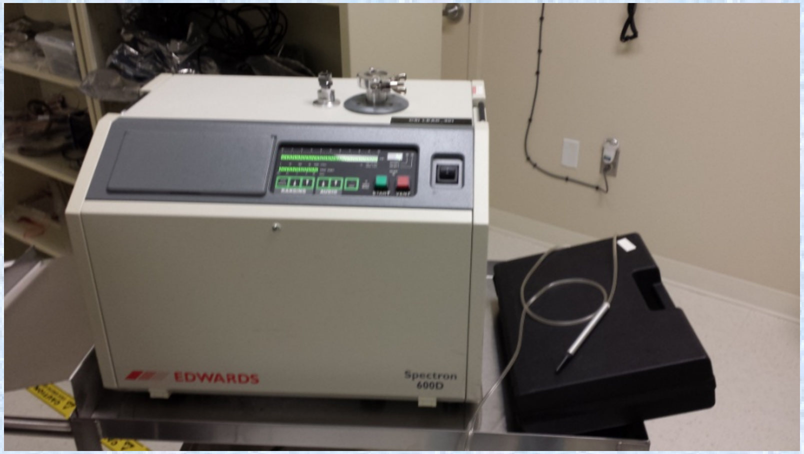
- Heat pipes are able to cool the laser with a total input load of 199.5 W
  - 3.6 J design point corresponds to a load of 180 W
  - Peak of diode emission ~792 nm at -30°C chiller setpoint

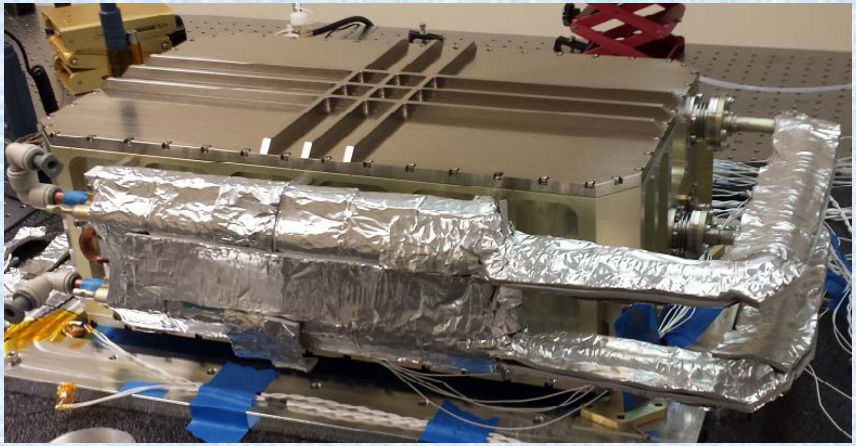


750 µs, 150 A, -30 deg C Emission Spectrum



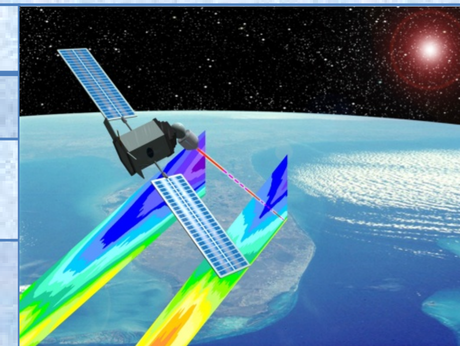
Initial Pressure Test





- **Filled sealed housing with ~5 psi of helium**
- **Used helium sniffer around all joints and screws to look for leaks**
- **None found meaning structure seals are sufficient for the thermalvac test**

Advancements Dramatically Lower Risk of Winds Space Mission



Past		Today	
525 km		400 km	
12 cross-track positions		2 cross-track positions	
1 shot measurement		Multiple shot accumulation	
Continuously rotating 1.5 m telescope		4 stationary 0.5 m telescopes	
Single coherent Doppler lidar		Dual coherent & direct hybrid Doppler lidar	
Gas laser		Solid-state eyesafe laser	
20 mJ 2-micron solid state energy		1200 mJ 2-micron solid state energy	
Space required energy = 20 J		Space required energy = 0.25 J	Conductively Cooled Laser
Energy deficit = 1,000		Energy surplus = 5	

➢ **From a 20-J, 10-Hz gas laser with 1.5-m diameter rotating telescope, to a 0.25-J, 10-Hz solid-state eyesafe laser with non-moving 0.5-m telescopes!**

Questions?