Compact, Engineered, 2-Micron Coherent Doppler Wind Lidar Prototype for Field and Airborne Validation

IIP-04-0072

“Doppler Aerosol WiNd lidar (DAWN)"

Interim Review #1 (6 months)

Michael J. Kavaya
NASA Langley Research Center

michael.j.kavaya@nasa.gov

23 June 2006
IIP Key Personnel

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Michael J. Kavaya</td>
<td>NASA LaRC</td>
<td>PI</td>
</tr>
<tr>
<td>Dr. Farzin Amzajerdian</td>
<td>NASA LaRC</td>
<td>Co-I, coherent lidar receiver lead</td>
</tr>
<tr>
<td>Dr. Grady J. Koch</td>
<td>NASA LaRC</td>
<td>Co-I, overall lidar system lead &amp; field demonstration lead</td>
</tr>
<tr>
<td>Mr. Ed A. Modlin</td>
<td>NASA LaRC</td>
<td>Technician</td>
</tr>
<tr>
<td>Dr. Upendra N. Singh</td>
<td>NASA LaRC</td>
<td>Co-I, LRRP PI</td>
</tr>
<tr>
<td>Mr. Bo. C. Trieu</td>
<td>NASA LaRC</td>
<td>Mechanical and system engineering</td>
</tr>
<tr>
<td>Dr. Jirong Yu</td>
<td>NASA LaRC</td>
<td>Co-I, pulsed transmitter laser lead</td>
</tr>
<tr>
<td>Dr. Yingxin Bai</td>
<td>SAIC</td>
<td>Laser design</td>
</tr>
<tr>
<td>Mr. Mulugeta Petros</td>
<td>STC</td>
<td>Laser design</td>
</tr>
<tr>
<td>Mr. Paul Petzar</td>
<td>SAIC</td>
<td>Electronic Design</td>
</tr>
<tr>
<td>Mr. Karl Reithmaier</td>
<td>SAIC</td>
<td>Opto-mechanical design</td>
</tr>
</tbody>
</table>

Also many thanks to Brian Killough, Keith Murray, Garnett Hutchinson, and Ken Anderson
<table>
<thead>
<tr>
<th>Mission</th>
<th>Measurement</th>
<th>Technique</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Science: Weather, Climate</td>
<td>Earth Vertical <strong>Wind</strong> Profiles</td>
<td>Scanning Doppler Lidar</td>
<td>Pulsed, 2-Micron, Ho Laser</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Science: Climate</td>
<td>Earth Vertical <strong>CO₂</strong> Concentration Profiles</td>
<td>Scanning DIAL Lidar</td>
<td>Pulsed, 2-Micron, Ho Laser</td>
</tr>
<tr>
<td>Science &amp; Exploration: Atmos. Char., EDL</td>
<td>Mars Vertical <strong>Density</strong> Profiles</td>
<td>DIAL Lidar (CO₂)</td>
<td>Pulsed, 2-Micron, Ho Laser</td>
</tr>
<tr>
<td>Science &amp; Exploration: Atmos. Char., EDL</td>
<td>Mars Vertical <strong>Wind</strong> Profiles</td>
<td>Scanning Doppler Lidar</td>
<td>Pulsed, 2-Micron, Ho Laser</td>
</tr>
<tr>
<td>Science: Climate</td>
<td>Earth Vertical <strong>Aerosol</strong> Concentration Profiles</td>
<td>Backscatter Lidar</td>
<td>Pulsed, 2-Micron, Ho Laser</td>
</tr>
<tr>
<td>Science &amp; Exploration: Atmos. Char., EDL</td>
<td>Mars Vertical <strong>Dust</strong> Profiles</td>
<td>Backscatter Lidar</td>
<td>Pulsed, 2-Micron, Ho Laser</td>
</tr>
</tbody>
</table>
The state-of-the-art 2-micron coherent Doppler wind lidar breadboard at NASA/LaRC will be engineered and compactly packaged consistent with future aircraft flights. The packaged transceiver will be integrated into a coherent Doppler wind lidar system test bed at LaRC. Atmospheric wind measurements will be made to validate the packaged technology.

This will greatly advance the coherent part of the hybrid Doppler wind lidar solution to the need for global tropospheric wind measurements.
IIP and the Global Tropospheric Wind Profiles Roadmap

2-Micron Coherent Doppler Lidar

- Laser Technology: 1988
- Diode Pump Technology: 1993
- Inj. Seeding Technology: 1996
- High Energy Technology: 1997
- Conductive Cooling Technology: 1999
- Compact Packaging: 2005
- Packaged Lidar Ground Demo: 2006

- Autonomous Oper. Technol.
- Space Qualif.
- Lifetime Validation
- Pre-Launch Validation
- 3-Yr. Lifetime Validation
- Demo, NPOESS
- Threshold, 400 km

Aircraft Operation

- UAV Operation
- Autonomous Oper. Technol.

0.355-Micron Direct Doppler Lidar

- Laser Technology: 2006
- Diode Pump Technology
- Inj. Seeding Technology
- Conductive Cooling Technology
- High Energy Technology
- Compact Packaging: 2006
- Packaged Lidar Ground Demo: 2006

- Laser Risk Reduction Program
- Ground-Based Risk Reduction (IPO)
- 2 micron Doppler wind aircraft flights
- 1 micron altimetry space missions
- Pump Laser Diode Advancement
- Dual Wavelength Telescope & Scanner

Past Funding

IIP-2004 Projects

Optional
IIP TRL Advancement

“4 → 5”

- **Space Qualification Tests**
- **Lifetime Demonstration**
- **Aircraft Validation**
- **Compact, Engineered Packaging**

**TRL 9**: Actual system “flight proven” through successful mission operations

**TRL 8**: Actual system completed and “flight qualified” through test and demonstration (Ground or Flight)

**TRL 7**: System prototype demonstration in a space environment

**TRL 6**: System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

**TRL 5**: Component and/or breadboard validation in relevant environment

**TRL 4**: Component and/or breadboard validation in laboratory environment

**TRL 3**: Analytical and experimental critical function and/or characteristic proof-of-concept

**TRL 2**: Technology concept and/or application formulated

**TRL 1**: Basic principles observed and reported
## IIP and the LaRC Development of Pulsed, 2-Micron Laser Technology For Space

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-Category/Date</th>
<th>6/02</th>
<th>9/02</th>
<th>2/03</th>
<th>4/03</th>
<th>11/03</th>
<th>2/05</th>
<th>12/05</th>
<th>LRRP</th>
<th>IIP</th>
<th>SPACE DEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demonstrated</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Side-Pumped, LuLiF)</td>
<td>Pulse Energy (J)</td>
<td>0.135</td>
<td>0.355</td>
<td>0.095</td>
<td>0.626</td>
<td>0.1/</td>
<td>1/1.5</td>
<td>1.2</td>
<td>0.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(in double pulse)</td>
<td>/0.66</td>
<td></td>
<td>1.05</td>
<td></td>
<td>0.073</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse Rate (Hz)</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>2/10</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>5-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Efficiency (%)</td>
<td>3.65</td>
<td>3.66</td>
<td>2.57</td>
<td>4.10</td>
<td>2.78</td>
<td>5/6.2</td>
<td>6.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Laser Component</strong></td>
<td>Oscillator</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Preamplifier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Amplifiers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 x 2-pass</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 x 2-pass</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Laser Mode</strong></td>
<td>Q-Switched</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double Q-Switched</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injection Seedsed=SLM</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>All liquid amp</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Partially conductive</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>All cond w/o heat pipe</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>All cond w/ heat pipe</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pump Diodes</strong></td>
<td>C Package</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A package</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AA package</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>G package</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Packaging</strong></td>
<td>Laboratory Table</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compact, Engineered</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## IIP Re-Plan, Fall 2005

<table>
<thead>
<tr>
<th>Original Plan</th>
<th>Proposed Replan</th>
<th>Citation/Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contracts</td>
<td>$1850K to Raytheon over 3 years (450/650/750) for packaging the lidar transceiver</td>
<td>$1800K to in-house effort with small contracts as needed for packaging the lidar transceiver</td>
</tr>
<tr>
<td>Starting Point</td>
<td>Some Raytheon IRAD spending during past few months</td>
<td>Completed compact design from $600K LRRP task in FY05</td>
</tr>
<tr>
<td>Lidar Transceiver Pulse Energy</td>
<td>Packaging 100 mJ design</td>
<td>Packaging 250 mJ design</td>
</tr>
<tr>
<td>Packaged Transceiver Specifications Guaranteed</td>
<td>No (contractor will not include IRAD in SOW per 12/2/05 comments on SOW)</td>
<td>Yes</td>
</tr>
<tr>
<td>Hardened for Future Post-IIP Aircraft Flight</td>
<td>Not included in NASA funding; promised IRAD effort may do some hardening</td>
<td>Flight-designed; ready for passenger compartment flights; ready for 60 Kft pressure</td>
</tr>
<tr>
<td>Electronics Advancement</td>
<td>No planned effort</td>
<td>Yes, compact laser control electronics included; heading towards high altitude &amp; autonomous operation electronics</td>
</tr>
<tr>
<td>External-to-Transceiver Thermal Management</td>
<td>No work planned outside of packaged transceiver</td>
<td>Custom-designed chiller/pump in addition to packaged transceiver</td>
</tr>
<tr>
<td>Autonomous Operation Sensors And Electronics</td>
<td>No planned effort</td>
<td>Novel quad detector in laser cavity to monitor alignment</td>
</tr>
<tr>
<td>Delivery Schedule</td>
<td>32 months after start</td>
<td>30 months after start</td>
</tr>
</tbody>
</table>
IIP – Scope of the Effort
Pulsed Doppler Wind Lidar Measurement Scenario
Pulsed Doppler Wind Lidar System

Lasers and Optics

Electronics

Computer, Data Acquisition, and Signal Processing (including software)
Lasers and Optics Portion

Lidar Transceiver (to be engineered under IIP)

- Transmitter Laser
- Receiver

- Pol. Plate
- λ/4 Plate
- BS
- T/R Switch

Large Optics (telescope, scanner)
Receiver

From T/R Switch

Photodetector

Seed Oscillator or Local Oscillator
IIP- Milestones & Schedule

**Year 1 (12/20/05 - 12/20/06)**
- ~ 1/1/06: Complete packaged transceiver requirements document
- NOW: Conceptual DR
- PDR

**Year 2 (12/20/06 - 12/20/07)**
- Demo prototype breadboard transmitter
- CDR
- Demo performance of engineered oscillator

**Year 3 (12/20/07 - 12/20/08)**
- Complete lab testing of engineered transceiver
- Integrate engineered transceiver into testbed
- Complete test of engineered transceiver in lidar testbed
Coherent Doppler Wind Lidar Technique
What Is “Coherent” Lidar?
Benefits Of The LO Laser

- Heterodyne gain effectively eliminates signal shot noise, thermal or Johnson noise, dark-current noise, and amplifier noise. LO spatial filtering eliminates background light noise.

- Translation of optical frequency to radio frequency allows signal processing with mature and flexible electronics and software, and reduces 1/f noise.

- Extremely narrow bandpass filter using electronics or software rejects even more noise.

- Frequency of beat signal is proportional to the target velocity - truly a direct measurement of velocity.
Benefits Of The LO Laser

• High accuracy
• High photon efficiency
• No intensity measurements needed

“heterodyne detection can allow measurement of the phase of a single-frequency wave to a precision limited only by the uncertainty principle”

Michael A. Johnson and Charles H. Townes
Optics Communications 179, 183 (2000)
1 μs (150m) Of Lidar Data And Its Spectrum

“Good” Wind Estimate

True wind, frequency = 10 m/s, 10 MHz
Effect Of SNR On Velocity Estimation

Rod Frehlich, Stephen Hannon, Sammy Henderson

Actual lidar data
6000 shots at 4.9 Hz

Unsuccessful or “bad” wind estimates; uniformly distributed over “allowed” velocity range

Top = Figure 4, R = 1 km, high SNR

Bottom = Figure 5, R = 5 km, low SNR
Example of coherent lidar velocity estimator performance

Example plots are for a maximum likelihood estimator.

These curves ‘slide’ up and down the x-axis as a function of lidar design.

Maximum and minimum values and shape of each will vary with lidar parameters. However ‘S’ shape and the relationship between the two curves are characteristic of all advanced coherent lidar velocity estimators.

Theory and experiment agree to within 5%.

Shot Accumulation Improves Velocity Estimation
Trade Sensitivity For Time/Range/Resolution

1 pulse
no accumulation

Actual lidar data
R = 5 km “low SNR”
6000 shots at 4.9 Hz
Doppler Wind Lidar Measurement Geometry: 833 km

Return light: t+6.6 ms, 49 m, 6.8 μrad

7.4 km/s

Second shot: t+100 ms, 744 m, 103 μrad

First Aft Shot t + 106 s

90° fore/aft angle in horiz. plane

833 km

984 km

492 km

348 km

45°

30°

34.4°

180 ns (27 m) FWHM (76%)

17 m (86%)

492 km

348 km

348 km

2 lines LOS wind profiles

1 line “horiz” wind profiles

25 m

120 shots = 12 s = 78 km

1/10 s = 658 m
Space-Based Coherent Lidar Wind Measurement

LO Laser
- Frequency Stability

Pulsed Laser
- Wavelength
- Spectrum
- Temporal Profile
- PRF

Atmosphere
- Wind Turbulence
- Wind Shear
- Backscatter Gradients
- Wind Uniformity
- Vertical Wind
- Clouds

SNR

Radial Wind Velocity Estimates

Shot Management

Horizontal Wind Velocity Estimates

Spatial Coverage, Angle Diversity

Azimuth Angle Scanning

Data Product
Doppler Lidar Firsts Relevant to this IIP

1960 – laser demonstrated
1964 – CO₂ laser demonstrated
1967 – CW CO₂ laser wind measurement
1971 – airborne CW CO₂ laser wind measurement
1977 – pulsed CO₂ laser wind measurement
1984 – airborne pulsed CO₂ laser wind measurement
1988 – pulsed Nd:YAG laser wind measurement
1991 – pulsed Tm,Ho:YAG laser wind measurement
1997-9 – SPARCLE (canceled)
1998 – ESA begin ADM
2002 – begin NASA Laser Risk Reduction Program*
2003 – 2-micron pulsed laser reaches 1000 mJ*
2005 – selection of IIP winds proposals*
1999 – airborne CO₂ pulsed laser reaches 1000 mJ
1994 – airborne CO₂ pulsed laser reaches 600 mJ
1994 – airborne 2-micron pulsed laser wind measurement
1994 – 2-micron pulsed laser reaches 100 mJ
1978 – winds from space feasibility study (scheduled shuttle flight in 1983)
# IIP Packaged Transceiver Requirements

<table>
<thead>
<tr>
<th>Category</th>
<th>Requirement</th>
<th>Goal (if different) and/or Space Requirement</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Architecture</td>
<td>Master Oscillator Power Amplifier (MOPA)</td>
<td></td>
<td>High energy, beam quality, optical damage</td>
</tr>
<tr>
<td>Laser Material</td>
<td>Ho:Tm:LuLiF</td>
<td></td>
<td>High energy, high efficiency, atmospheric transmission</td>
</tr>
<tr>
<td>Nominal Wavelength</td>
<td>2.053472 microns</td>
<td></td>
<td>Atmospheric transmission</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>150 mJ</td>
<td>250 (space)</td>
<td>Computer modeling of measurement performance</td>
</tr>
<tr>
<td>Pulse Repetition Frequency</td>
<td>10 Hz</td>
<td>10-20 (space)</td>
<td>Shot accumulation, optimum laser diode array lifetime</td>
</tr>
<tr>
<td>Pulse Beam Quality</td>
<td>&lt; 1.4 x diffraction limit</td>
<td></td>
<td>Heterodyne detection efficiency influence</td>
</tr>
<tr>
<td>Pulse Spectrum</td>
<td>Single Frequency</td>
<td>Few MHz (space)</td>
<td>Frequency estimation process</td>
</tr>
<tr>
<td>Injection seeding success</td>
<td>95%</td>
<td>99%</td>
<td>Shot accumulation</td>
</tr>
<tr>
<td>Laser Heat Removal</td>
<td>Partial Conductively Cooled</td>
<td>FCC (space)</td>
<td>No liquid lines in space</td>
</tr>
<tr>
<td>Packaging</td>
<td>Compact, engineered</td>
<td>Aircraft ready Space qual. (space)</td>
<td>As ready as possible for aircraft follow on</td>
</tr>
</tbody>
</table>
Laser Design Considerations

- Laser wavelength
- Laser material
- Laser pumping geometry
- Laser cavity design
- Laser architecture
Why Ho: Tm: LuLiF

- **Why Ho laser?**
  - Tm lasers in 2-µm region have such a low gain cross-section ($\sigma_{em} \approx 10^{-20}$ cm²) that efficient, high-energy laser amplification is impossible without the risk of laser crystal or associated optics damage.
  - Ho lasers have large enough stimulated emission cross-section ($\sigma_{em} \approx 10^{-19}$ cm²) for effective amplification to obtain high-energy.

- **Why co-doped?**
  - Takes advantage of diode pumping for Tm lasers
  - Takes advantage of the efficient Tm 1:2 relaxation energy transfer process
  - Takes advantage of the high emission cross-section of Ho laser
**Why Ho:Tm:LuLIF — Cont.**

- **Why fluoride?**
  - Fluoride
    - Long upper laser level lifetime ~ 15 ms, store more energy
    - Low up-conversion loss
    - Higher emission cross-section
    - Naturally birefringent material, no depolarization loss
    - Negative $dn/dT$ -> weak thermal lensing
  - Garnet
    - Isotropic
    - Excellent thermo-mechanical properties

- **Why Lutetium?**
  - Lanthanide series ions
    - Lutetium, Yttrium, Gadolinium
  - Lutetium
    - Lutetium – larger crystal field
      - larger manifold stark splitting -> Small thermal population of ground state
Laser Architecture
Master Oscillator Power Amplifier (MOPA)

- Energy requirement
  - Single oscillator can’t produce required energy
- Beam quality
  - MOPA preserves the good beam quality
- Lifetime
  - Permits more derating of pump diodes
- Efficiency
  - Multiple pass amplifier improving the efficiency
- Optics Damage
  - Reducing intra-cavity fluence
Cavity Configuration

- **Linear Cavity**
  - Standing waves
  - Simple
  - Round trip - pass gain medium twice

- **Ring Cavity**
  - Traveling waves
  - No spatial hole burning in the gain - single mode
  - Long cavity needed to obtain narrow linewidth
  - Beneficial for injection seeding through output coupler
Pumping configuration

• Pumping geometry
  – Side Pumping
    » Power scaling
    » Uniform pumping
  – End Pumping
    » Easy thermal management
    » Easy to mode match
    » Higher pump density

• Single Longitudinal Mode
  – Interferometric mode selection
  – Monolithic design, short cavity
  – Injection seeding
Optical Bench

• Two options:
  26.5 x 23.0 x 7 inch single side
  26.5 x 11.5 x 7 inch double sided

• The split can be done such that the receiver optics and the seed laser on one side, and the power Oscillator amplifier on the other.

• Optical bench is water cooled, enclosed and dry purged.
LRRP Pulsed, 2-Micron Laser Transmitter Opto-Mechanical Design

- 3-m, bow-tie, unidirectional master oscillator power amplifier
- Seeding and receiver optics on reverse side
- Expect this hardware in about 8 weeks for LRRP
Seed Laser

CW seed laser

Seed laser driver
Oscillator features

- Injection seeded
- Cavity length >3m Ring
- Output coupler Reflectivity ~70%
- Diode pump lasers: 36 bars 100W/b conductive cooled
- crystal doped material length 21mm
- undoped LuLF length 15 mm
- Laser crystal cooling : H₂O, Methanol
- Tube size: 6mm OD 5mm ID AR coated for 792nm wedged 0.5° along c-axis AR coated for 2.053µm
- Laser rod ends
- Laser rod cylinder AR coated for 792nm
Oscillator Head
Oscillator cavity length

- Long cavity length is needed to obtain narrow linewidth
  - Pulse length is one of the critical parameters of a coherent Lidar.
  - A short pulse compromises frequency resolution while a long pulse compromises range resolution.
  - To meet the pulse length requirement, the oscillator length was changed from 2m to 3m. It prolongs the pulse width to near 200ns
  - The resonator has six mirrors and 8 bounces.
Amplifier features

- Pump energy: 7.2 Joules, 12x6 bar arrays with 100 watts/bar
- Diode laser: conductive cooled ‘AA’ Pkg
- Laser crystal: Ho:Tm:LuLF 0.5% Ho 6% Tm
- Doped Crystal length: 41 mm
- Ends diffusion bonded crystals: 15 mm undoped LuLF
- Laser crystal cooling: H₂O
- Flow tube size: 6 mm OD, 5 mm ID AR coated 792 nm
- Rod end surfaces: AR coated for 2.053 µm
- Laser cylinder: AR coated for 792 nm
- Path configuration: double pass
Amplifier Module
Proposed Transceiver “Box”

- Modular approach with injection seed & local oscillator separate from transceiver.
- Separate seed/LO allows flexibility to adapt to 3 measurements scenarios:
  - simple, fixed frequency LO for ground or low platform speed.
  - higher intermediate frequency for high platform speed.
  - swept LO for very high platform speed.
- DIAL of CO₂

Note: only optical paths are represented; electrical and water paths are not shown.
• baseline design for ground-based implementation.
• recommended for IIP demonstration.
• fiber-to-free space through AOM then back to fiber is disadvantageous—looking into fiber optic pigtailed AOM.
• could be packaged in rack-mount breadboard with fan for cooling (need thermal analysis).
Test Bed: Putting it all Together

- CW master oscillator
- AOM 105 MHz isolator
- 90% 10% 50/50 coupler
- Fiber optic port
- Turning mirror (deflects beam up toward scanner)
- Beam expander
- λ/4
- PBS
- Amplifier
- 50/50 coupler
- Pulsed laser: may be folded with more mirrors
- Resonance detector
- PZT Q-switch
- Injection seed
- Pulse monitor (on flip stage)
- Visible alignment laser
- Outgoing Pulse
- Atmospheric Return
- Injection Seed
- Pulse Monitor
- Local Oscillator
- λ/2
VALIDAR Scanner

- scanner is mounted on roof of laboratory trailer.
- 8-inch clear aperture.
- can be pointed or scanned in elevation/azimuth for hemispherical coverage.
- linked to data acquisition computer for automated profiling of wind.
VALIDAR Telescope

- off axis Dall-Kirkham design.
- 6-inch aperture
- 20X expansion
Data Acquisition and Processing System

CompactPCI Chassis

Scanner Control Computer

Lidar Transceiver

Analog Front End

Digitizer

Control Program

Host CPU

Storage Devices

Real-Time Display & User Interface

Outgoing Pulse

Lidar Return

RS-232

CompactPCI Bus

Digital Signal Processor--2 cards of 4 chips
Atmospheric Measurements
(will be better than this VALIDAR sample)

- jets
- virga
- rain enhancing backscatter

passage of frontal system
Installation of Laser Timing Device

• The Laser Timing Device was installed in the VALIDAR system and tested in complete lidar.

• Significance of this new hardware:
  – Reduces size, weight, and complexity of control electronics associated with laser transmitter.
  – Improves performance of injection seeding and offers simpler adjustment of parameters.
  – Allows implementation of double-pulsing with injection seeding.
  – Graphical user interface.
Simplification of Hardware

BEFORE

8 separate electronic boxes

AFTER

19” rack-mount enclosure, 1.75 inches high
# IIP Year 1 Financials

As of 6/8/06

<table>
<thead>
<tr>
<th></th>
<th>Budget</th>
<th>Committed</th>
<th>Obligated</th>
<th>Costed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FY05 Funds</strong></td>
<td>$175.0K</td>
<td>174.6K</td>
<td>115.9K</td>
<td>24.2K</td>
</tr>
<tr>
<td><strong>FY06 Total</strong></td>
<td>841.3K</td>
<td>317.4K</td>
<td>272.7K</td>
<td>111.3K</td>
</tr>
<tr>
<td>Labor*</td>
<td>189.5K</td>
<td>48.3K</td>
<td>48.3K</td>
<td>48.3K</td>
</tr>
<tr>
<td>G&amp;A</td>
<td>189.0K</td>
<td>29.1K</td>
<td>29.1K</td>
<td>29.1K</td>
</tr>
<tr>
<td>Service Pools</td>
<td>160.6K</td>
<td>33.9K</td>
<td>33.9K</td>
<td>33.9K</td>
</tr>
<tr>
<td>Procurement</td>
<td>296.9K</td>
<td>206.2K</td>
<td>162.4K</td>
<td>0</td>
</tr>
<tr>
<td>Travel</td>
<td>5.3K</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*1.45 FTE plan
0.57 FTE actual
Summary

• IIP project 6 months into 36 month effort
• On schedule and budget to date
• Leveraging LRRP work on compact laser in 05 and 06
• Plan on significant steps of compact, engineered packaging of state-of-the-art laser/lidar technology. TRL definitions do not reveal significant progress.
• Companion IIP at GSFC for noncoherent Doppler wind lidar will complement this project to permit hybrid DWL on aircraft and then in space
• Project very consistent with findings of NASA/ESTO Laser/Lidar Technology Requirements Working Group results (FY06). To be issued in final report
• Anticipate strong endorsement of global winds by NAS decadal study on earth sciences
• Same technology promises additional applications for earth and Mars
BACK UP
• used for aircraft.
• same as Option 1, except AOM offset is higher.
• system may require replacement of heterodyne photodetectors.
• aircraft speed and scanner angle are used to select a frequency to beat down heterodyne signal to bandwidth of data acquisition system.
• used with space mission with very high Doppler shifts from satellite motion. While IIP hardware would not be used for a space mission, useful system testing could be accomplished if this seed/LO option could be incorporated into system.
Solid State 2-micron Lasers

- Tm Lasers (pump diodes 780-805nm)
  - YAG, YLF, YAIO₃, YVO₄

- Ho:Tm Lasers (pump diodes 780-805nm)
  - LuLF, YLF, GdLF, YAG, YVO₄

- Tm pumped Ho lasers (pump diodes 780nm)
  - Tm solid state laser pumped Ho Laser
  - Tm fiber laser pumped Ho Laser

- Ho Lasers (pump diodes 1900nm)
  - YAG
Transceiver Environment Requirements

- **Platform:** ground-based (Airborne qualify-able)
- **Operational Temperature:** 0°C -30°C
- **Non-Operational Temperature:** -25°C; +50°C
- **Operating Altitude Range:** Sea level to 30,000 ft
- **Humidity:** <50% RH@25°C
- **Vibration:** 2.0 g-rms
- **Optical bench:** temperature controlled
- **Coolant Temperature:** 5°C
- **Coolant Flow**
  - Laser rod: 0.4 GPM
  - Diode Laser: 1.5 GPM
  - Bench: 1.5 GPM
- **Coolant Pressure:** 50 psi at 6 GPM

3/26/2008
Wind Lidar Block Diagram
Electronics Block Diagram

Digital circuits
Timing and control
(µcontroller FPGA)

Analog circuits
Sensors and signal conditioning

A.O. modulator

Pulsed diode
Laser driver

Computer interface

PZT driver

Seed laser driver

Q-S driver

Resonance
Humidity
Temperature
Energy interlock
Oscillator and Amplifier layout

THRU BENCH

SEED LASER

Q SWITCH

AMP OUTPUT THRU BENCH

2.865 mm SEPERATION

AMP

CAVITY LENGTH= 2012MM
REQUIRES 2 EXTRA MIRRORS

DIMS IN mm

533.400

215.900

325.000
1. Seed laser input
2. Fiber beam splitter
3. Collimator
4. Faraday isolator
5. ½ wave plate

6. Polarizer
7. Beamsteering optics
8. Receiver signal optics
9. Heterodyne monitor
10. Receiver detectors
11. AOM output
Transceiver integration with lidar

- CW master oscillator
- Isolator
- AOM (105 MHz)
- Oscillator
- Fiber optic port
- Turning mirror (deflects beam up toward scanner)
- Beam expander
- $\lambda/4$ beam expander

Transceiver
Sensors

• Optical detectors:
  Energy monitor (InGaAs or Pyroelectric)
  Temporal pulse and energy monitor
    (Photo electro-magnetic detector)
  Resonance detector (InGaAs)
  Seeding quality (InGaAs)
  Return signal (dual input InGaAs fiber coupled)

• Humidity sensors
• Temperature monitors
<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial mode</td>
<td>$\text{TEM}_{00}$ Gaussian</td>
</tr>
<tr>
<td>Output</td>
<td>$&gt;35\text{mw}$</td>
</tr>
<tr>
<td>Output isolation</td>
<td>$60\text{dB}$ fiber coupled</td>
</tr>
<tr>
<td>Additional protection:</td>
<td>$&gt;50\text{ dB}$ between the oscillator and the AO modulator</td>
</tr>
<tr>
<td>Fiber type</td>
<td>single mode polarization preserving</td>
</tr>
<tr>
<td>Fiber core diameter</td>
<td>$6\mu\text{m}$</td>
</tr>
<tr>
<td>Operating conditions</td>
<td>$20^\circ$ to $25^\circ\text{C}$ heat sink temperature</td>
</tr>
</tbody>
</table>
Seed Laser Linewidth Measurement

- Seed Laser 1
- Seed Laser 2
- Coupler
- Detector
- Spectrum Analyzer
Seed laser line width

Emission Bandwidth
13.11 kHz
10Hz Oscillator performance

Performance of 3m resonator

\[ y = -0.1464 + 0.073887x \quad R = 0.98893 \]

\[ y = -0.45074 + 0.20352x \quad R = 0.99948 \]

Pulse length as a function of pump energy

Output (J) vs. pump energy (J)

Pulse length (ns) vs. pump energy (J)
Amplifier Architecture

Half wave Plate  Faraday Isolator  Half wave Plate  Amplifier

Osc.
Double pass amplifier performance

![Graph showing 10Hz Amplifier Double-pass Performance]

- Probe = 95 mJ
- Rod temperature = 8°C

![Graph showing output with 5°C rod temperature]

- Probe = 101 mJ
- Double pass output @5°C
Preliminary layout (side 1)
Preliminary layout (side 2)
Optical Mirror Mount
Optical Component Mounts

AO modulator

Q-Switch