IIP Update: A Packaged Coherent Doppler Wind Lidar Transceiver

“Doppler Aerosol WiNd lidar (DAWN)”


to

Working Group on Space-Based Lidar Winds
Welches, OR
27 June 2006
## IIP Key Personnel

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Role</th>
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</thead>
<tbody>
<tr>
<td>Dr. Michael J. Kavaya</td>
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<td>PI</td>
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<tr>
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<td>Co-I, coherent lidar receiver lead</td>
</tr>
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<td>Co-I, overall lidar system lead &amp; field demonstration lead</td>
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<td>Technician</td>
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</tr>
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<td>Co-I, pulsed transmitter laser lead</td>
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<td>Laser design</td>
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<td>Mr. Mulugeta Petros</td>
<td>STC</td>
<td>Laser design</td>
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<td>Mr. Paul Petzar</td>
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<td>Electronic Design</td>
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<td>Mr. Karl Reithmaier</td>
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Also many thanks to Brian Killough, Keith Murray, Garnett Hutchinson, and Ken Anderson
### IIP Motivation

<table>
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<tr>
<th>Mission</th>
<th>Measurement</th>
<th>Technique</th>
<th>Technology</th>
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<tbody>
<tr>
<td><strong>Primary</strong></td>
<td><strong>Science: Weather, Climate</strong></td>
<td>Earth Vertical <strong>Wind</strong> Profiles</td>
<td>Scanning Doppler Lidar</td>
</tr>
<tr>
<td><strong>Secondary</strong></td>
<td><strong>Science: Climate</strong></td>
<td>Earth Vertical <strong>CO₂</strong> Concentration Profiles</td>
<td>Scanning DIAL Lidar</td>
</tr>
<tr>
<td></td>
<td><strong>Science &amp; Exploration: Atmos. Char., EDL</strong></td>
<td>Mars Vertical <strong>Density</strong> Profiles</td>
<td>DIAL Lidar (CO₂)</td>
</tr>
<tr>
<td></td>
<td><strong>Science &amp; Exploration: Atmos. Char., EDL</strong></td>
<td>Mars Vertical <strong>Wind</strong> Profiles</td>
<td>Scanning Doppler Lidar</td>
</tr>
<tr>
<td></td>
<td><strong>Science: Climate</strong></td>
<td>Earth Vertical <strong>Aerosol</strong> Concentration Profiles</td>
<td>Backscatter Lidar</td>
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<tr>
<td></td>
<td><strong>Science &amp; Exploration: Atmos. Char., EDL</strong></td>
<td>Mars Vertical <strong>Dust</strong> Profiles</td>
<td>Backscatter Lidar</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**

- 2 micron laser (1988)
- Diode Pump Technology (1993)
- Inj. Seeding Technology (1996)
- High Energy Technology (1997)
- Conductive Cooling Techn. (1999)
- Compact Packaging 2005
- Packaged Lidar Ground Demo. 2006

**1 micron laser**

- Inj. Seeding Technology
- Conductive Cooling Techn.
- High Energy Technology
- Compact Packaging 2006
- Packaged Lidar Ground Demo. 2006

**0.355-Micron Direct Doppler Lidar**

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

**Ground-Based Risk Reduction (IPO)**

- 2 micron Doppler wind aircraft flights
- 1 micron altimetry space missions
- Pump Laser Diode Advancement

**Lidar Perf. Simulations**

- Dual Wavelength Telescope & Scanner

**OSSE’s**

- Past Funding
- Laser Risk Reduction Program
- IIP-2004 Projects

**Optional**
IIP TRL Advancement

“4 → 5”

Compact, Engineered Packaging

Aircraft Validation

Space Qualification Tests

Lifetime Demonstration

System Test, Launch & Operations

System/Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

Basic Technology Research

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 (Side-Pumped, LuLiF)</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>Pulse Energy (J) (in double pulse)</td>
<td>0.135</td>
<td>0.355 /0.6</td>
<td>0.095</td>
<td>0.626 /1.05</td>
<td>0.1 /0.073</td>
<td>1/1.5</td>
<td>1.2</td>
<td></td>
<td>0.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<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></td>
<td>10</td>
<td>5-10</td>
<td></td>
</tr>
<tr>
<td>Efficiency (%) (O-O)</td>
<td>3.65</td>
<td>3.66</td>
<td>2.57</td>
<td>4.10</td>
<td>2.78</td>
<td>5/6.7</td>
<td>6.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

### Laser Component
- Oscillator
- Preamplifier
- Amplifiers: 1 x 2-pass, 2 x 2-pass

### Laser Mode
- Q-Switched
- Double Q-Switched
- Injection Seeded=SLM

### Cooling
- All liquid
- Partially conductive
- All cond w/o heat pipe
- All cond w/ heat pipe

### Pump Diodes
- C Package
- A package
- AA package
- G package

### Packaging
- Laboratory Table
- Compact, Engineered
IIP- Milestones & Schedule

Year 1
12/20/05 - 12/20/06
~ 1/1/06

- Complete packaged transceiver requirements document
- Conceptual DR CoDR
- 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
## 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>
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: \( \text{H}_2\text{O}, \text{Methanol} \)
- Tube size: 6mm OD 5mm ID AR coated for 792nm
- Laser rod ends: wedged 0.5° along c-axis AR coated for 2.053\( \mu \text{m} \)
- 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 for 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 4 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.
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
Seed/LO Option 1

- 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 → 90% → AOM 105 MHz → 10% → turning mirror (deflects beam up toward scanner) → λ/4 → PBS → λ/2 → Outgoing Pulse

90% → PBS → 50/50 coupler → 10% → fiber optic port

50/50 coupler → amplifier → aspheric optic (if necessary) → PZT → Ho:Tm:LuLiF → Q-switch → resonance detector – pulse monitor (on flip stage)

Visible alignment laser → Q-switch → Ho:Tm:YLF → PZT → Q-switch → resonance detector – pulse monitor (on flip stage)

Injection Seed → 50/50 coupler → CW master oscillator

Beam expander → 90% → fiber optic port

Connector → 10% → 90% → 50/50 coupler
VALIDAR Telescope

- off axis Dall-Kirkham design.
- 6-inch aperture
- 20X expansion
• 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.
Data Acquisition and Processing (already built)

Scanner Control Computer

Lidar Transceiver

Analog Front End

Digitizer

Real-Time Display & User Interface

CompactPCI Chassis

Control Program

Host CPU

Storage Devices

RS-232

Outgoing Pulse

Lidar Return

Digital Signal Processor--2 cards of 4 chips
Atmospheric Measurements
(will be better than this VALIDAR sample)
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
Project Motto 1

• Be Prepared
Project Motto 2

• Walk before you run
BACK UP
IIP – Scope of the Project
Pulsed Doppler Wind Lidar Measurement Scenario

Lidar System

Propagation Path (Atmosphere)

Target (Atmospheric Aerosols)
Lidar System

Lasers and Optics

Electronics

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

Lidar Transceiver (to be engineered under IIP)

Transmitter Laser

Receiver

λ/4 Plate

Pol.

BS

T/R Switch

Large Optics
(telescope, scanner)
Transmitter Laser

- Pulsed Laser Diode Array
- Pulsed Laser Diode
- Seed Oscillator
- CW Laser Diode
- AOM
- Pulsed Laser Oscillator
- To T/R Switch
- Pulsed Laser Amplifier
- Pulsed Laser Diode Array

Pulsed Component
Receiver

From T/R Switch

Photodetector

Seed Oscillator or Local Oscillator

Pulsed Component
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 ($\sigma_{em} \sim 10^{-20}$ cm$^2$) 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 ($\sigma_{em} \sim 10^{-19}$ cm$^2$) 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.