Status of Laser/Lidar Working Group Requirements

by

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to

Working Group on Space-Based Lidar Winds
June 27-30, 2006
Welches, OR
Atmospheric Dynamics (Winds)

Science Requirements Subgroup

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(S) = Science lead
(T) = Technology lead

Authors also worked in Technology Challenge subgroups:
• Laser Transmitters
• Detection, Processing, Optics
• First WG meeting: Nov. 8-9, 2005
• Second WG meeting: Dec. 14-15, 2005
• Community Forum: Jan. 10, 2006
• Third WG meeting: Jan. 11, 2006
• Fourth WG meeting: Feb. 7-8, 2006
• Writing of final report …
• June 9, 2006: draft copy of final report available at
  http://esto.nasa.gov/lwg/lwg.htm
## Space Wind Measurement Requirements - 1

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Demo</th>
<th>Threshold</th>
<th>Objective</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical depth of regard (DOR)</td>
<td>0-20</td>
<td>0-20</td>
<td>0-30</td>
<td>km</td>
</tr>
<tr>
<td>Vertical resolution:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropopause to top of DOR</td>
<td>Not Req.</td>
<td>Not Req.</td>
<td>2</td>
<td>km</td>
</tr>
<tr>
<td>Top of BL to tropopause (~12 km)</td>
<td>2</td>
<td>1</td>
<td>0.5</td>
<td>km</td>
</tr>
<tr>
<td>Surface to top of BL (~2 km)</td>
<td>1</td>
<td>0.5</td>
<td>0.25</td>
<td>km</td>
</tr>
<tr>
<td>Number of collocated LOS wind measurements for horiz(^A) wind calculation</td>
<td>2 = pair</td>
<td>2 = pair</td>
<td>2 = pair</td>
<td>-</td>
</tr>
<tr>
<td>Horizontal resolution(^A)</td>
<td>350</td>
<td>350</td>
<td>100</td>
<td>km</td>
</tr>
<tr>
<td>Number of horizontal(^A) wind tracks(^B)</td>
<td>2</td>
<td>4</td>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td>Velocity error(^C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Above BL</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>m/s</td>
</tr>
<tr>
<td>In BL</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>m/s</td>
</tr>
<tr>
<td>Minimum wind measurement success rate</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>%</td>
</tr>
<tr>
<td>Temporal resolution (N/A for single S/C)</td>
<td>N/A</td>
<td>12</td>
<td>6</td>
<td>hours</td>
</tr>
<tr>
<td>Data product latency</td>
<td>N/A</td>
<td>2.75</td>
<td>2.75</td>
<td>hours</td>
</tr>
</tbody>
</table>

\(^A\) Horizontal winds are not actually calculated; rather two LOS winds with appropriate angle spacing and collocation are measured for an “effective” horizontal wind measurement. The two LOS winds are reported to the user.

\(^B\) The cross-track measurements do not have to occur at the same along-track coordinate; staggering is OK.

\(^C\) Error = 1\(\sigma\) LOS wind random error, projected to a horizontal plane; from all lidar, geometry, pointing, atmosphere, signal processing, and sampling effects. The true wind is defined as the linear average, over a 100 x 100 km box (or 175 km or 25 km) box centered on the LOS wind location, of the true 3-D wind projected onto the lidar beam direction provided with the data.

(Original errata that have been corrected) (Added/clarified requirements during NASA ESTO ESTIPS Laser/Lidar Working Group)
# Space Wind Measurement Requirements - 2

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Demo</th>
<th>Threshold</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical location accuracy of LOS wind measurements</td>
<td>1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Horizontal location accuracy of LOS wind measurements</td>
<td>5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Allowed angular separation of LOS wind pair, projected to a horizontal plane</td>
<td>30-150</td>
<td>30-150</td>
<td>30-150</td>
</tr>
<tr>
<td>Maximum allowed horizontal separation of LOS wind pair</td>
<td>50</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Maximum horizontal extent of each horizontal^A wind meas.</td>
<td>175</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Minimum horizontal cross-track width of regard of wind measurements</td>
<td>N/A</td>
<td>±400</td>
<td>±625</td>
</tr>
<tr>
<td>Maximum cross-track spacing of adjacent cross-track locations</td>
<td>N/A</td>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>Maximum design horizontal wind speed: Above BL</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>Within BL</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Design 1σ wind turbulence level: Above BL</td>
<td>1</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Within BL</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Max. LOS wind unknown bias error, proj. to a horiz. plane</td>
<td>1</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Minimum design a priori velocity knowledge window, projected to a horizontal plane (using nearby wind measurements and contextual information)</td>
<td>26.6</td>
<td>26.6</td>
<td>26.6</td>
</tr>
<tr>
<td>Design cloud field:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer from 9-10 km, extinction coefficient</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Layer from 2-3 km, 50% of lidar shots untouched, 50% blocked</td>
<td>50, random</td>
<td>50, random</td>
<td>50, random</td>
</tr>
<tr>
<td>Aerosol backscatter coeff.: 2 vertical profiles provided</td>
<td>Provided</td>
<td>Provided</td>
<td>Provided</td>
</tr>
<tr>
<td>Aerosol backscatter: Probability density function (PDF) PDF width</td>
<td>Lognormal</td>
<td>Lognormal</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Provided</td>
<td>Lognormal</td>
<td>Provided</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Provided</td>
<td>Lognormal</td>
<td>Provided</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Atmospheric extinction coefficient: 2 vertical profiles provided</td>
<td>Provided</td>
<td>Provided</td>
<td>Provided</td>
</tr>
<tr>
<td>Orbit latitude coverage</td>
<td>N/A</td>
<td>80N to 80S</td>
<td>80N to 80S</td>
</tr>
<tr>
<td>Downlinked data</td>
<td>All</td>
<td>All</td>
<td>TBD</td>
</tr>
</tbody>
</table>

(Original errata that have been corrected) (Added/clarified requirements during NASA ESTO ESTIPS Laser/Lidar Working Group)
Atmospheric Winds

Recommended Roadmap

Past

1 Micron Altimetry

2 Micron Winds

0.355 & 2 Micron Winds
Space-like Geometry & Scanning

0.355 & 2 Micron Winds
NPOESS
833 km
Demo

0.355 & 2 Micron Winds
NASA
400 km
Threshold, 3 yr.
Acknowledgements

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Outline

• Definition Process

• Investment Priority Analysis

• Technology Roadmap
Working Group Charter

Develop a strategy for targeted technology development and risk mitigation efforts at NASA by leveraging technological advancement made by other government agencies, industry and academia, and move NASA into the next logical era of laser remote sensing by enabling critical Earth Science measurements from space.
Requirement Definition Process

1. Science Requirements
   - Atmospheric Composition
   - Atmospheric Dynamics
   - Topography (Land, Ice, Biomass)

2. Measurement Scenarios
   - Laser Transmitter
   - Detection, Processing, Optics

3. Technology Challenges
   - Data Acquisition
   - Data Utilization

4. Capability Breakdown Structure (CBS)

5. Prioritization Filter

6. Roadmap

7. Phases:
   - Phase A: Science
   - Phase B: Technology
   - Phase C: Integration
Laser Remote Sensing Techniques & Applications

Doppler Lidar
- Wind Field

Backscatter Lidar
- Clouds
- Aerosols
- Phytoplankton Physiology
- Ocean Carbon/Particle Abundance

Differential Absorption Lidar (DIAL)
- Carbon Dioxide
- Ozone, Water Vapor

High-Precision Ranging & Altimetry
- Geodetic Imaging
- Vegetation Structure/Biomass
- Earth Gravity Field
Weather

**Tropospheric Winds** - Doppler Lidar recognized as the *only* means for acquiring wind profiles with required precision (1 m/s, 100-km horizontal resolution).

**Water Vapor Profile** - DIAL recognized as the *only* technique for global moisture profile at high resolution (0.5 km vertical by 50 km horizontal) in the boundary layer, essential for understanding severe storm development.
Measurements *Primarily* Achieved by Laser Remote Sensing

**Atmospheric Composition**

**Tropospheric CO$_2$ Profile** - DIAL is the only technique for high precision profiling of CO2 (0.3% mixing ratio, 2-km vertical scale), essential for understanding the global carbon cycle and global warming trends.

**High Resolution Clouds & Aerosol** - Backscatter lidar is the *only* technique for high vertical resolution (50m) measurements of optical properties of clouds and aerosols including planetary boundary height, cloud base, cloud top, cloud depolarization, and aerosol scattering profiles needed in climate modeling.

**High Resolution Tropospheric Ozone Profile** - DIAL is the *only* technique for global tropospheric ozone profiling with high resolution (1-2 km vertical, 100 km horizontal), essential for understanding atmospheric processes in the troposphere.
Measurements *Primarily* Achieved by Laser Remote Sensing

Carbon Cycle & Ecosystems

3D Biomass - Lidar Altimetry is the only technique for profiling 3D vegetation canopies to the required vertical accuracy of 0.5 m and horizontal resolution of 5-20m

Phytoplankton Physiology & Ocean Carbon Abundance - Lidar is the *only* method for measuring particle profiles in the oceans’ mixed layer of 5m resolution depth or better, necessary to understand how oceanic carbon storage and fluxes contribute to the global carbon cycle
High Resolution Ice Surface Topography - Lidar Altimetry is the only technique for profiling ice surface topography and changes of less than 1 cm/year, essential for understanding climate change.
Earth Gravity Field 3D - Improved range measurements provided by laser interferometry will improve Earth gravity field observation to less than 100 km and 10-day resolution with an accuracy of less than 1 cm equivalent surface water height.

Terrestrial Reference Frame - Improved satellite laser ranging network will provide a factor of 5-10 improvement in reference frame and satellite precision orbit determination over current measurements.
Outline

• Definition Process

• Investment Priority Analysis
  • Prioritization Criteria
  • Analysis

• Technology Roadmap
Technology Prioritization Criteria

1. Scientific Impact
2. Societal Benefit
3. Measurement Scenario Uniqueness
4. Technology Development Criticality
5. Technology Utility
6. Measurement Timeline
7. Risk Reduction
Scientific Impact

The degree to which the proposed measurement via lidar technique will impact our understanding of the Earth System and will help answer the overarching questions defined in NASA Earth Science Research strategy.

**Tropospheric Winds** --> Severe Weather Prediction

**Tropospheric CO₂ Profile** --> Global Warming Trends and Air Quality

**High Resolution Polar Ice Topography Change** --> Climate Change Prediction

**3D Biomass** --> Carbon Cycle, Sources/Sink, Climate Change Prediction

**Phytoplankton Physiology** --> Oceanic Carbon Cycle
Societal Benefit

The degree to which the proposed measurement has the potential to improve life on Earth.

Near-Term Benefits

1. Severe Weather Prediction (Trop Wind)
2. Air Quality/Assessment of Global Warming (CO₂)
3. Long Term Climate Change (Ice mass, Biomass, CO₂)

Long-Term Benefits

Prediction of Hurricane Tracks Using Trop Wind Data

Sep 14, 1999 06Z – Sep 19, 1999 00Z every 6 hrs
Credit: Ardizzone & Terry 2006
Measurement Scenario Uniqueness

Whether Lidar technique is the *primary or unique technique* for making the proposed measurement.

- Tropospheric Winds
- CO₂ Vertical Profile
- Vegetation Biomass
- High Resolution Ice Surface Topography
- Phytoplankton Physiology & Functional Groups
- High Spectral Resolution Aerosol
- Ocean Carbon/Particle Abundance
- Earth Gravity Field
- Terrestrial Reference Frame

Also appeared under previous criteria
Technology Development Criticality

Whether the development of the proposed technology *enables new and critical measurement capabilities* as opposed to provide incremental improvement in the measurement.

**Technology Criticality Priority**

- Enabling
- Cost Reducing
- Performance Enhancing
The degree to which the technology makes significant contribution to more than one measurement application, i.e. is cross cutting in utility.

**Transmitter Technology Utility**

![Graph showing technology utility for different transmitter requirements and technologies.](image-url)
Measurement Timeline

Determined by the time horizon *when a particular measurement is needed*, as articulated in NASA’s Earth Science Research Strategy.
Risk Reduction

The degree to which the new technology *mitigates the risk of mission failure.*

- Laser Transmitters present the greatest development challenge and pose the greatest risk.
- Risk reduction laser transmitter technologies are of highest priority.
Filtering Requirements Leads to Technology Priorities

Science Applications
- Tropospheric Winds
- Ice Topography
- Tropospheric CO₂
- 3D Biomass
- Phytoplankton Physiology

Priority Filter
- Science Impact
- Societal Benefit
- Scenario Uniqueness
- Technology Criticality
- Technology Utility
- Timeline
- Risk Reduction

Enabling Technologies
- Laser Transmitters
- Detection, Processing, Optics
- Data Acquisition & Utilization

Emerging Technology Priorities

Roadmap
Required Laser Transmitter Capabilities

1. Pulsed Lasers

- Beam Director
- Wavelength Converters
- Pulse Repetition Frequency (Hz)
- Energy Per Pulse (mJ)

2. CW Lasers

- Fiber or Bulk Material
- Bulk Material Domain
- Tropospheric Winds
- Phytoplankton
- Ice Mass
- Biomass

Wavelength:
- 1 micron
- 1.5 micron
- 2 micron

Vis-UV
Wavelength Converters

- 5 W
- 10 W
- Fiber
# Laser Transmitter Priorities

<table>
<thead>
<tr>
<th>1-100 W, 0.1-50 mJ, 1 micron Fiber or Bulk Laser</th>
<th>100 W, 100Hz, 1 micron Laser</th>
<th>1-100 W, 1.5 micron Fiber Laser</th>
<th>5-20 W, 2 micron Laser</th>
<th>Wavelength Converters</th>
<th>Beam Director</th>
</tr>
</thead>
<tbody>
<tr>
<td><a href="#">Image</a> Trop Wind DEMO</td>
<td><img src="#" alt="Image" /> Ice Mass</td>
<td><img src="#" alt="Image" /> 3D Biomass</td>
<td><img src="#" alt="Image" /> Phytoplankton</td>
<td>100 W, 100Hz, 1 micron Laser</td>
<td>100 W, 100Hz, 1 micron Laser</td>
</tr>
<tr>
<td>1-100 W, 0.1-50 mJ, 1 micron Fiber or Bulk Laser</td>
<td>100 W, 100Hz, 1 micron Laser</td>
<td>1-100 W, 1.5 micron Fiber Laser</td>
<td>5-20 W, 2 micron Laser</td>
<td>Wavelength Converters</td>
<td>Beam Director</td>
</tr>
<tr>
<td>1 J/100 Hz, single freq @ 1064 nm, WPE 6-8%</td>
<td>0.1 mJ/75kHz @ 1064 nm, 5ns pulse, WPE 10%</td>
<td>100 mJ/100 Hz @ 1064 nm, pulselength ~3 ns</td>
<td>0.5 J/10 Hz, single freq, WPE &gt; 1.4%</td>
<td>340 mJ/100 Hz @ 355 nm, &gt;40% harmonic conv. from 1064 nm</td>
<td>20/200 &amp; 500 mJ/20–100 Hz @ 532 nm conv eff. &gt;50%</td>
</tr>
<tr>
<td>0.1 mJ/75kHz @ 1064 nm, 5ns pulse, WPE 10%</td>
<td>100 mJ/100 Hz @ 1064 nm, pulselength ~3 ns</td>
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<td>1 J/100 Hz, single freq @ 1064 nm, WPE 6-8%</td>
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</tr>
<tr>
<td>1 J/100 Hz, single freq @ 1064 nm, WPE 6-8%</td>
<td>100 mJ/100 Hz @ 1064 nm, pulselength ~3 ns</td>
<td>1 J/20 Hz double pulsed, WPE 3-5% AND/OR 5 W CW</td>
<td>5-20 W, 2 micron Laser</td>
<td>Wavelength Converters</td>
<td>Beam Director</td>
</tr>
<tr>
<td>10 W cw OR 0.1 mJ/100 kHz</td>
<td>1 J/20 Hz double pulsed, WPE 3-5% AND/OR 5 W CW</td>
<td>10 W CW @ 1.6 micron 1064-nm pumped OPO</td>
<td>100 W, 100Hz, 1 micron Laser</td>
<td>100 W, 100Hz, 1 micron Laser</td>
<td>100 W, 100Hz, 1 micron Laser</td>
</tr>
<tr>
<td>1000 beam positions across 1-2° FOV</td>
<td>1000 beam positions across 1-2° FOV</td>
<td>1000 beam positions across 1-2° FOV</td>
<td>1000 beam positions across 1-2° FOV</td>
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<td>1000 beam positions across 1-2° FOV</td>
</tr>
</tbody>
</table>

* Current TRL designated in lower right corner.
Required Lidar Receiver Capabilities

- **Alignment Maintenance**
  - Transmit/Receive Alignment (µrad)
  - 2, 4, 6, 8, 10

- **Wavelength:**
  - 1.5 micron
  - 2 micron

- **Detection Systems**
  - Scanning Systems
  - Detection Electronics

- **Transmit/Receive Alignment (µrad)**
  - 2 4 6 8 10

- **Aperture Diameter (m)**
  - 1 2 3

- **Large Telescopes**
  - < 25 kg/m²

- **Detectors**
  - Quantum Efficiency (%)
  - 0 10 20 30 40 50 60 70 80 90 100

- **Specialty Optics**
  - Optical Filters
  - Spectral Analyzers

- **Applications:**
  - Tropospheric Winds
  - Biomass
  - Ice Mass
  - Phytoplankton
  - CO₂
Lidar Receiver Priorities

* Current TRL designated in lower right corner.
Data Acquisition and Utilization Priorities

Air/Ground Validation Sys.
Adaptive targeting
Intelligent Sensor H&S
On-board Sensor Control

Cal/Val ≤ 1 hr*
OSSE ≥ 3 instruments
Cal/val < Days
Plan & Execution: <3 hr
Laser life diagnosis < days
Control sys. error = 4 μrad

Cal/val < Days
Cal/Val: <1% Error
Laser life prognosis < days

*Required for operational weather and air pollution measurement systems

* Current TRL designated in lower right corner.
Outline

• Definition Process
• Investment Priority Analysis
• Technology Roadmap
Overall Recommendation

• Highest priority measurement(s) must be identified at the Agency level first.

• Technology Requirements for each measurement in the area of transmitters, DPO, and DADU are tightly coupled.

• Technology development to satisfy the priority measurement(s) must then targeted and coordinated in the three categories in order to get maximum return on investment.
Kavaya/Gentry Conclusions

• Fast-paced experience
• Impossible to AND {include everyone who has something to contribute, afford the effort, come to an agreement, finish}; therefore accept the imperfections of it all
• Draft report strongly endorses technology development for tropospheric wind mission
• Tall poles not explicitly captured: coherent winds = laser lifetime, alignment; direct winds = scanner, photon efficiency
• Still time to (quickly) give corrections to draft report
• Future NASA opportunities for funding might reflect the priorities of this report
• Many thanks to Ramesh Kakar for participating & advocating
• Many thanks to Winds WG members who contributed