Concept for a U.S. Space-Based Wind Lidar: Status and Current Activities

JCSDA and EMC Seminar
July 28, 2009

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Outline

- Background
- Which Upper Air Observations Do We Need for NWP?
- Forecast Impact Results
- Need for Improved Accuracy of Transport Estimates for Climate Applications
- A U.S. Wind Lidar Effort – Why now?
- Concept for a U.S. Space-Based Wind Lidar
- Recent Advances in Technology Readiness
- Concluding Remarks
The National Research Council (NRC) Decadal Survey report published in 2007 recommended a global wind mission - The NRC Weather Panel determined that a hybrid Doppler Wind Lidar (DWL) in low Earth orbit could make a transformational impact on global tropospheric wind analyses

Independent modeling studies at NCEP, ESRL, NASA and ECMWF show tropospheric wind profiles to be the single most beneficial measurement now absent from the Global Observing System

A number of recent papers have suggested that the general circulation of the atmosphere has considerable variability on decadal timescales, some of which may be due to greenhouse forcing.\(^1\,^2\) Each of those studies, however, relies on imperfect climate models and datasets that are limited in their ability to provide a complete picture of large-scale circulation change.


ESA planning to launch first DWL in June 2011: Atmospheric Dynamics Mission (ADM)
- Only has a single perspective view of the target sample volume
- Only measures line-of-sight (LOS) winds

A joint NASA/NOAA/DoD global wind mission (Global Wind Observing Sounder – GWOS) offers the best opportunity for the U.S. to demonstrate a wind lidar in space in the coming decade
- Measures profiles of the horizontal vector wind for the first time
Numerical weather prediction requires independent observations of the mass (temperature) and wind fields.

The global three-dimensional mass field is well observed from space.

No existing space-based observing system provides vertically resolved wind information.
Current Upper Air Mass & Wind Data Coverage

Upper Air Mass Observations

Upper Air Wind Observations
Observations Needed as a Function of Forecast Length

Based on a chart for NW Europe produced by the European Center for Medium-Range Weather Forecasts.
Wind Lidar OSSE Results with NCEP Global Model (Masutani et al., 2006)

Red: Conventional data + TOVS data only
Green: Conventional data + TOVS + wind lidar

Top: Northern Hemisphere 500 hPa height anomaly correlation

Middle: Northern Hemisphere 200 hPa wind field – synoptic waves only (n = 10 – 20)

Bottom: Northern Hemisphere 850 hPa wind field – synoptic waves only

Note: Only random error applied to TOVS data; results with coarse resolution (T62) model
ESRL Regional Lidar OSSE Results - Assimilation of Lidar Obs + Lidar Obs in Boundary Conditions

- >6% improvement for all forecast times
- Positive impact greater for non-raob initial times
- Contributions from lidar assimilation and boundary conditions nearly additive
- From briefing by S. Weygandt et al.
Simulated DWL Impact on a Hurricane Track Forecast (R. Atlas et al.)

Hurricanes Tracks

**Green**: Actual track

**Red**: Forecast beginning 63 h before landfall with current data

**Blue**: Improved forecast for same time period with simulated DWL data

Note: A significant positive impact was obtained for both land falling hurricanes in the 1999 data; the average impact for 43 oceanic tropical cyclone verifications was also significantly positive.
Forecast Impact Using Actual Aircraft Lidar Winds in ECMWF Global Model (Weissmann and Cardinali, 2007)

- DWL measurements reduced the 72-hour forecast error by ~3.5%
- This amount is ~10% of that realized at the oper. NWP centers worldwide in the past 10 years from all the improvements in modelling, observing systems, and computing power
- Total information content of the lidar winds was 3 times higher than for dropsondes

Diff in RMS of fc-Error: RMS(fc_en5t - an_eiz3) - RMS(fc_eiz3 - an_eiz3)
Lev=500, Par=z, fcDate=20031115-20031128 00/12 UTC, Step=96
NH=-4.14 SH= 6.82 Trop= 0.05 Eur=-14.54 NAmer= -6.13 NAtl= 2.84 NPac= -7.9

Green denotes a positive impact

Mean (29 cases) 96 h 500 hPa height forecast error difference (Lidar Exper minus Control Exper) for 15 - 28 November 2003 with actual airborne DWL data. The green shading means a reduction in the error with the Lidar data compared to the Control. The forecast impact test was performed with the ECMWF global model.
Observed Track of Typhoon Nuri and Path of Navy P3 Aircraft (P3DWL) during T-PARC 2008 (D. Emmitt)
Flight Level Winds from P3DWL
(Provided by D. Emmitt)

A –G denote location of dropsondes

Zhaoxia Pu and Lei Zhang, Department of Atmospheric Sciences, University of Utah
G. David Emmitt, Simpson Weather Associates, Inc.

Model: Mesoscale community Weather Research and Forecasting (WRF) model
Data: Doppler wind Lidar (DWL) profiles during T-PARC for the period of 0000UTC –0200 UTC 17 August 2008
Forecast Period: 48-h forecast from 0000UTC 17 August 2008 to 0000UTC 19 August 2008
Control: without DWL data assimilated into the WRF model.
Data Assimilation: With DWL data assimilated into the WRF model

Data impact: Control vs. Data assimilation

- Assimilation of DWL profiles eliminated the northern bias of the simulated storm track.
- Assimilation of DWL profiles resulted in a stronger storm that is more close to the observed intensity of the storm.
Improved reanalysis data sets are needed to provide a more accurate environmental data record to study global warming; for example, recent studies\(^1\,^2\) indicate that the recent dramatic reduction in sea ice extent observed in the Arctic may be due, in large part, to heat transport into the Arctic, but this finding is based on reanalysis wind data with large uncertainty in the Arctic because of lack of actual wind measurements.

The measurement of accurate, global winds is critical for climate monitoring:

“The nation needs an objective, authoritative, and consistent source of . . . reliable. . . climate information to support decision-making. . .”\(^3\)

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\(^1\) JCSDA Seminar by Erland Kallen, April 23, 2009


\(^3\) NOAA Annual Guidance Memorandum, Internal Draft, May 10, 2009
### Why Wind Lidar? Societal Benefits at a Glance…

**Improved Operational Weather Forecasts**

**Civilian**
- Hurricane Track Forecast
- Flight Planning
- Air Quality Forecast
- Homeland Security
- Energy Demands & Risk Assessment
- Agriculture
- Transportation
- Recreation

**Military**
- Ground, Air & Sea Operations
- Satellite Launches
- Weapons Delivery
- Dispersion Forecasts for Nuclear, Biological, & Chemical Release
- Aerial Refueling

- Estimated potential benefits ~$940M per year*
- Including military aviation fuel savings ~$130M per year**
- Roughly 1/3 of the $940M per year total is due to reduced airline fuel consumption which supports the “Energy Security and Sustainability” goal in the NOAA AGM***

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** AF aviation fuel usage estimate provided by Col. M. Babcock
*** NOAA Annual Guidance Memorandum, Internal Draft, May 10, 2009
OSSEs and experiments with actual airborne wind lidar measurements (Pu et al., 2009; Weissmann and Cardinali, 2007) show these data will improve forecast skill.

The European Space Agency will launch the ADM/Aeolus lidar wind measuring satellite in June 2011.

NOAA will have access to ADM/Aeolus data, but NOAA needs to start developing the data assimilation capability now.
Concept for a U.S. Space-Based Wind Lidar

Global Wind Observing Sounder (GWOS)
Measuring Wind with a Doppler Lidar

DOPPLER RECEIVER - Multiple flavors - Choice drives science/technology trades
- Coherent or heterodyne aerosol Doppler receiver
- Direct detection molecular Doppler receiver

Coherent
2 micron

355 nm

Direct detection

TELESCOPE

LASER TRANSMITTER

MOLECULES

AEROSOLS

WIND

Backscattered Spectrum

\[ \Delta \nu_{DOP} \]

Aerosol (\( \lambda^{-2} \))
Molecular (\( \lambda^{-4} \))
Frequency
GWOS Hybrid DWL Technology Solution

- Direct Detection Doppler Lidar
  - Uses molecular backscatter
  - Meets threshold requirements when aerosols not present

- Coherent Doppler Lidar
  - Uses aerosol backscatter
  - High accuracy winds when aerosols & clouds present

Overlap allows:
- Cross calibration
- Best measurements selected in assimilation process

Altitude Coverage vs Velocity Estimation Error
The coherent subsystem provides very accurate (<1.5 m/s) observations when sufficient aerosols (and clouds) exist.

The direct detection (molecular) subsystem provides observations meeting the threshold requirements above 2 km, clouds permitting.

When both sample the same volume, the most accurate observation is chosen for assimilation.

The combination of direct and coherent detection yields higher data utility than either system alone.
GWOS Measurement Capability

24 km
21 km
18 km
16 km
14 km
12 km
10 km
8 km
6 km
4 km
2 km
1.5 km
1 km
0.5 km
0 km

Direct Detection

Coherent Detection

Velocity Accuracy
GWOS Coverage

• Around 600 radiosonde stations (black) provide data every 12 h

• GWOS (blue) would provide ~3200 profiles per day
Simulated GWOS Measurements from Cloud Returns
(Provided by D. Emmitt)

Observation source and errors
Blue: Coherent w/ < 1.5 m/s
Red: Direct w/ < 3.0 m/s;
10% duty cycle

With background aerosol concentrations

With enhanced aerosol concentrations
Simulated GWOS Synergistic Vector Wind Profiles*
(Provided by D. Emmitt)

Background aerosol mode

Coherent aerosol and direct detection molecular channels work together to produce optimum vertical coverage of bi-perspective wind measurement

Green: both perspectives from coherent system
Yellow: both perspectives from direct molecular
Blue: one perspective coherent; one perspective direct

Enhanced aerosol mode

Green: both perspectives from coherent system
Yellow: both perspectives from direct molecular
Blue: one perspective coherent; one perspective direct

50% more vector observations from hybrid technologies

* When two perspectives are possible
Hybrid Doppler Wind Lidar Measurement Geometry: 400 km

Return light: t+3.9 ms, 30 m, 4.4 microrad
7.7 km/s

Second shot: t+200/10 ms
1535/77 m, 227/11 microrad
48.7°

First Aft Shot
First Aft Shot
t + 190 s
90° fore/aft angle
in horiz. plane

Ground spot speed: 7.2 km/s
45° fore/aft angle
in horiz. plane

45 deg azimuth Doppler shift from S/C velocity
±3.7 GHz
±22 GHz

Max nadir angle to strike earth
70.2 deg

RIGHT, FORE
585 km

RIGHT, AFT

400 km

292 km

414 km

292 km

5 m (86%)
180 ns (27 m)
FWHM (76%)

60/1200 shots = 12 s = 87 km
0.2/0.01 s = 1444/72 m
(2/0.355 microns)

2 lines LOS wind profiles
1 line “horizontal” wind profile
Hybrid Doppler Wind Lidar
Measurement Geometry: 400 km

1 Vector Horizontal Wind Profile vs. Altitude
Hybrid Doppler Wind Lidar
Measurement Geometry: 400 km

350 km/217 mi
53 sec
Along-Track Repeat
“Horiz. Resolution”

586 km/363 mi
ADM-Aeolus

- Doppler Wind Lidar
- Cross-track HLOS winds
- $\sigma_{\text{HLOS}} (z) = 2-3 \text{ m/s}$
- Profiles 0–30 km@0.5-2 km
- Once every 200 km length
- Aerosol and molecular measurement channel
- Dawn-dusk polar-orbiter
- Launch date June 2011

www.esa.int/esaLP/LPadmaeolus.html
(Stoffelen et al., BAMS, 2005)
## GWOS Comparison with ADM

<table>
<thead>
<tr>
<th>Attribute</th>
<th>ADM</th>
<th>GWOS</th>
<th>NWOS*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Altitude</td>
<td>400</td>
<td>400</td>
<td>824</td>
</tr>
<tr>
<td>Orbit Inclination</td>
<td>98 sun-synch</td>
<td>98 sun-synch</td>
<td>98 sun-synch</td>
</tr>
<tr>
<td>Day/Night</td>
<td>Night only</td>
<td>Day/Night</td>
<td>Day/Night</td>
</tr>
<tr>
<td>Number of LOS</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Profiles per orbit</td>
<td>~200 single LOS</td>
<td>~229 vector</td>
<td>~250 vector</td>
</tr>
<tr>
<td>Components per profile</td>
<td>Single –Model estimated second component</td>
<td>Two components - full horizontal vector</td>
<td>Two components - full horizontal vector</td>
</tr>
<tr>
<td>Horizontal Resolution</td>
<td>200 km between single LOS profile one side of ground track</td>
<td>350 km with full profile both sides of ground track</td>
<td>350 km with full profile both sides of ground track</td>
</tr>
<tr>
<td>Vertical Resolution</td>
<td>PBL 0.25 – 0.5 km Troposphere 1 km</td>
<td>PBL 0.25 - 0.5 km Tropo 1 – 2 km</td>
<td>PBL 0.25 - 0.5 km Tropo 1 – 2 km</td>
</tr>
</tbody>
</table>

* NexGen NPOESS Wind Observing Sounder
Roadmap to Operational Space-Based DWL on NexGen NPOESS

GWOS (2017)
- Demo 3-D global wind measurements
- Operational 3-D global wind measurements

ESA ADM (2011)
- Single LOS global wind measurements

TODWL (2002 - 2008)
- DWL Airborne Campaigns, ADM Simulations, etc.

NexGen NPOESS (2026)

TODWL: Twin Otter Doppler Wind Lidar [CIRPAS NPS/NPOESS IPO]
ESA ADM: European Space Agency-Advanced Dynamics Mission (Aeolus) [ESA]
GWOS: Global Winds Observing System [NASA/NOAA/DoD]
Recent Advances in Technology Readiness

- Recent infusion of NASA funding has accelerated advances in both direct and coherent wind lidar technologies.
- Initial airborne campaign of hybrid instrument (TWiLiTE--GSFC-led; DAWN--LaRC-led) planned for Fall 2010.
- The DWL whitepaper (Hardesty et al., 2005), submitted to the NRC Committee on the Decadal Survey, was based on lidar technology readiness circa 2001, is now significantly outdated, and will be updated in the next few months.
- Recent technology advances will also be highlighted in a new *BAMS* article to be prepared in the near future.
HDWL Technology 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. 2007

Past Funding
- Laser Risk Reduction Program
- IIP-2004 Projects
- ROSES-2007 Projects

2008 - 2012
- TRL 5
- Aircraft Operation DC-8

2011 - 2013
- TRL 6 to TRL 7
- Autonomous Aircraft Oper. WB-57
- Space Qualified
- Lifetime Validation
- Pre-Launch Validation

2017
- GWOS
- Operational NexGen NPOESS

2026

0.355-Micron Direct Doppler Lidar

- 1 micron laser
- Diode Pump Technology
- Inj. Seeding Technology
- Conductive Cooling Techn.
- High Energy Laser Technology
- Compact Laser Packaging 2007
- Compact Molecular Doppler Receiver 2007
Concluding Remarks

- A U.S. GWOS mission would fill a critical gap in our capability to measure global wind profiles, and,
- Significantly improve the skill in forecasting high impact weather systems globally (i.e., hurricanes, mid-latitude storms, etc.),
- Reduce the uncertainty in transport estimates derived from reanalysis data for climate applications,
- Provide major societal benefits, both civilian and military,
- Make a transformational impact on global tropospheric wind analyses, according to the NRC Weather Panel, and provide major benefits to the NASA, NOAA and DoD missions, and to the Nation
- Recent lidar technology advances are consistent with a GWOS mission in 2017, if the funding is available

- The upcoming ESA ADM in 2011 will provide the first direct wind measurements from space and serve as a prototype for the development of the data assimilation capability for a U.S. winds mission
Backup Slides
## DWL Measurement Requirements

<table>
<thead>
<tr>
<th>Vertical depth of regard (DOR)</th>
<th>NASA-NOAA-DoD Science GWOS</th>
<th>NPOESS Operational NexGen</th>
<th>km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical resolution:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropopause to top of DOR</td>
<td>0-20</td>
<td>0-20</td>
<td></td>
</tr>
<tr>
<td>Top of BL to tropopause (~12 km)</td>
<td>4</td>
<td>3</td>
<td>km</td>
</tr>
<tr>
<td>Surface to top of BL (~2 km)</td>
<td>2</td>
<td>1</td>
<td>km</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.5</td>
<td>km</td>
</tr>
<tr>
<td>Horizontal resolution&lt;sup&gt;A&lt;/sup&gt;</td>
<td>350</td>
<td>350</td>
<td>km</td>
</tr>
<tr>
<td>Minimum Number of horizontal&lt;sup&gt;A&lt;/sup&gt; wind tracks&lt;sup&gt;B&lt;/sup&gt;</td>
<td>2</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Number of collocated LOS wind measurements for horizontal&lt;sup&gt;A&lt;/sup&gt; wind calculation</td>
<td>2 = pair</td>
<td>2 = pair</td>
<td>-</td>
</tr>
<tr>
<td>Velocity error&lt;sup&gt;C&lt;/sup&gt; Above BL</td>
<td>3</td>
<td>3</td>
<td>m/s</td>
</tr>
<tr>
<td>In BL</td>
<td>2</td>
<td>2</td>
<td>m/s</td>
</tr>
<tr>
<td>Minimum wind measurement success rate&lt;sup&gt;D&lt;/sup&gt;</td>
<td>50</td>
<td>50</td>
<td>%</td>
</tr>
</tbody>
</table>

<sup>A</sup> 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.  
<sup>B</sup> The 4 cross-track measurements do not have to occur at the same along-track coordinate; staggering is OK.  
<sup>C</sup> Error = 1s 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 centered on the LOS wind location, of the true 3-D wind projected onto the lidar beam direction provided with the data.  
<sup>D</sup> Scored per vertical layer per LOS measurement not counting thick clouds