Improved Weather Prediction, Climate Understanding, and Weather Hazard Mitigation through Global Profiling of Horizontal Winds with a Pulsed Doppler Lidar System

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1 Abstract

This concept paper suggests a way for the US to move forward with space-based global wind measurements in a way that is consistent with the current status of the Doppler wind lidar technology and techniques, the status of the wind measurement requirements, and the mission already underway by the European Space Agency.

2 The Challenge

The science and operational communities of the United States and other countries greatly need global profiles of wind velocity for many applications; especially improved weather prediction, greater understanding of climate issues, and mitigation of weather hazards to the population. The high value of winds to improved weather prediction is highlighted by the fact that it is ranked as the highest priority unmet measurement by NPOESS/IPO, which is a joint office representing DOD, NOAA, and NASA[1]. A very strong case for tropospheric wind profiling from space has been made in the scientific literature[2-6]. It has also been shown to have a very positive economic benefit to the country[7-8]. The wind measurement requirements, in order for the wind observations to be useful through assimilation into computer models, were defined in 2001 by a scientific panel led by NASA and NOAA. An abbreviated version of these requirements is shown in Tables 2 and 3, with errata in the original version fixed here (see red text). The “Threshold” and “Objective” requirements were stated to provide a “noticeable” and “significant” improvement, respectively. Meeting these wind measurement requirements from Earth orbit, especially the coverage, resolution, velocity error, and number of simultaneous tracks of horizontal vector wind, is a challenge. Not all these requirements will be met simultaneously by any existing or planned sensing systems, as outlined in Table 1.

3 The Solution

Ground-based experimental wind measurements with both the coherent-detection and the direct-detection Doppler wind lidar (DWL) techniques started in the 1960s. Wind measurements from aircraft using coherent detection began in 1972, and continue to this day. The idea of measuring global wind profiles with orbiting DWL systems has been pursued in several studies by NOAA, NASA, and the DOD since the mid 1970s. One shortcoming of almost all the studies over 25 years has been the lack of well defined requirements, a problem now mostly solved by the 2001 NASA/NOAA requirements. Without all the exhaustive entries in Tables 2 and 3, the degrees of

Table 1. Inadequacy of other wind measurement techniques to meet the NASA/NOAA requirements

Wind Measurement Technique	**Comparison to NASA/NOAA Requirements**	**Comments**
Rawinsonde Launches	Inadequate horizontal coverage. Only 1706 reports worldwide on 3/31/04	Biased to land and developed countries. Expensive per measurement
Cloud Motion Winds	Inadequate vertical and horizontal coverage	Height assignment errors
Orbiting Scatterometers	Inadequate vertical coverage and horizontal coverage	Biased to oceans and surface layer
Aircraft Reported Winds (ACARS)	Inadequate vertical and horizontal coverage	Biased to aircraft routes only
Ground Radar Profilers	Inadequate horizontal coverage	Biased to land and developed countries. Expensive per measurement
Water Vapor Tracked Winds	Inadequate accuracy and vertical coverage	Height assignment errors

Table 2. NASA/NOAA Global Tropospheric Wind Sounder Science and Operational Wind Data Product Requirements Issued Oct. 16, 2001 – Primary Requirements

	Threshold	**Objective**	
Vertical depth of regard (DOR)	0-20	0-30	km
Vertical resolution:			
Tropopause to top of DOR	Not Req.	2	km
Top of BL to tropopause (~12 km)	1	0.5	km
Surface to top of boundary layer (~2 km)	0.5	0.25	km
Number of collocated LOS wind measurements for the horizontal[A] wind calculation	2 = pair	2 = pair	-
Horizontal resolution[A]	350	100	km
Number of horizontal[A] vector wind tracks[B]	4	12	-
Velocity error[C] Above BL	3	2	m/s
In BL	2	1	m/s
Minimum wind measurement success rate	50	50	%
Temporal resolution	12	6	hours
Data product latency	2.75	2.75	hours

[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 for assimilation into models.
[B] The cross-track measurements do not have to occur at the same along-track coordinate; staggering is OK.
[C] Error = 1σ 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.

freedom available to DWL mission designers permitted many 10s of dBs of “slop” in the required size of the DWL, creating a problem for mission comparisons and management decision making. The early studies, e.g., LAWS (Laser Atmospheric Wind Sounder), baselined the coherent detection DWL technique, a very high pulse energy CO_2 gas laser, a continuously turning conical scanner, and wind profile measurements from each laser shot. During the 1990s, the advancement of solid-state lasers and the decline of budgets brought many simultaneous changes. The coherent DWL technique changed from the CO_2 gas laser to the new solid-state

Table 3. NASA/NOAA Global Tropospheric Wind Sounder Science and Operational Wind Data Product Requirements Issued Oct. 16, 2001 – Secondary Requirements

	Threshold	**Objective**	
Vertical location accuracy of line-of-sight (LOS) wind measurements	0.1	0.1	km
Horizontal location accuracy of LOS wind measurements	0.5	0.5	km
Allowed angular separation of LOS wind pair, projected to a horizontal plane	30-150	30-150	degree
Maximum allowed horizontal separation of LOS wind pair	35	35	km
Maximum horizontal extent of each horizontal[A] wind measurement	100	25	km
Minimum horizontal cross-track width of regard of wind measurements	±400	±625	km
Maximum cross-track spacing of adjacent cross-track locations	350	100	km
Maximum design horizontal wind speed: Above BL Within BL	 75 50	 100 50	 m/s m/s
Design 1σ wind turbulence level: Above BL Within BL	 1.2 1	 1.4 1	 m/s m/s
Maximum LOS wind unknown bias error, projected to a horizontal plane	0.1	0.05	m/s
Minimum design a priori velocity knowledge window, projected to a horizontal plane (using nearby wind measurements and contextual information)	26.6	26.6	m/s
Design cloud fields: Layer from 9-10 km, extinction coefficient Layer from 2-3 km, 50% of lidar shots untouched, 50% blocked	 0.14 50, random	 0.14 50, random	 km^{-1} %
Aerosol backscatter coefficient: 2 vertical profiles provided (background & enhanced)	Provided	Provided	$m^{-1}sr^{-1}$
Aerosol backscatter: Probability density function (PDF) PDF width	 Lognormal Provided	 Lognormal Provided	 m sr $m^{-1}sr^{-1}$
Atmospheric extinction coefficient: 2 vertical profiles provided (background & enhanced)	Provided	Provided	km^{-1}
Orbit latitude coverage	80N to 80S	80N to 80S	Degree
Downlinked data	All raw data	TBD	-

laser at 2-microns wavelength. The advancement in the Nd:YAG laser including frequency tripling to the UV region, allowed direct detection to be considered for the space mission. Both coherent and direct DWL techniques, in an effort to lower costs, power, and aperture size, changed to a step-stare conical scan which allows many laser shots to be combined for each wind profile measurement.

Technology development and mission design work by NASA, NOAA, academia, and private industry since the issuance of the 2001 requirements show that the gap between DWL technology capability and the "Threshold" requirements is rapidly shrinking[9-11], and it is quite reasonable to now consider a "pathfinder" or "demonstrator" DWL mission by the US. The pulsed DWL technique, in conjunction with a step-stare conical scanner, is uniquely able to provide the desired horizontal and vertical resolution. The short wavelength of the laser light, as compared to microwaves, permits much smaller "antennas" than a radar system. With a smaller "antenna" or mirror, conical scanning is enabled leading to the desired horizontal vector winds.

The stricter "Objective" requirements, compared to the "Threshold" requirements, present a much harder challenge. Considering only the stricter requirements for vertical and horizontal resolution, number of wind tracks, and velocity error leads to a rough estimate of a factor of 20 larger lidar emitted optical power-aperture area product. Neither DWL technique is close to meeting these requirements today. We believe that this should <u>not deter</u> the first mission, due to the many things that will be learned from a first mission about the technology, the DWL technique, the atmosphere, about assimilating and using the data, and about the necessary requirements for the future. In view of the unanticipated usefulness of the data from many prior orbited sensors, it would not be surprising at all to learn from the first mission that "significant" results are produced by wind measurements meeting much relaxed requirements compared to the "Objective" requirements above. Recent results of Observing System Simulation Experiments (OSSEs) support this prediction of a better return on investment than reflected in the requirements.

4 DWL Technologies Offer Multiple Solution Paths for a Complex Situation

The consensus of NASA and NOAA is that, in the long term, the desired wind profile measurements can best be made by a <u>hybrid</u>, pulsed, DWL system; that is, a lidar system consisting of <u>both</u> a coherent (heterodyne) detection DWL system and a direct (noncoherent) detection DWL system working together in a complementary fashion. The coherent DWL would make highly accurate wind profile measurements in atmospheric regions having an aerosol backscatter coefficient above a certain threshold, and in areas with clouds. The direct DWL would make less accurate wind measurements, and would require a larger receiver mirror and more electrical power for the laser, but would obtain data from molecular backscatter in the mid- and upper-troposphere where there are fewer aerosols.

In summary, the coherent DWL is strong on accuracy, mirror size, electrical power, and clouds, but weak on coverage in the mid and upper troposphere. Conversely, the direct DWL is strong on coverage in cloud free regions, but weak on velocity accuracy, mirror size, and electrical power. In even briefer language, the coherent DWL is coverage challenged, and the direct DWL is accuracy and accommodation challenged. Both lidar techniques would provide excellent vertical resolution, and much more coverage of the earth than is available today. This is why the hybrid DWL concept is attractive. It does not appear feasible at this time for an affordable coherent DWL instrument and mission to consistently measure wind profiles up the required heights of 20 and 30 km. It also does not seem feasible for an affordable direct DWL instrument and mission to simultaneously meet the requirements for velocity error, vertical resolution, horizontal resolution, and number of wind tracks. Even should the laser, large telescope, and large scanner technologies advance to the point of being able to do the whole job with either DWL technique alone, it is doubtful that accommodating the power, volume, mass, heat removal, and momentum compensation would be affordable.

There are several additional important points:

- The 2001 requirements do not discuss any prioritization. If one assumes that coverage is the most important requirement, and falling short of other requirements (velocity error, horizontal and vertical resolution, number of wind tracks, scanning to obtain vector winds) is acceptable, then direct DWL appears most promising. If one assumes velocity accuracy, resolution, scanning, and minimum spacecraft accommodation needs is most important, and falling short on coverage is acceptable, then coherent DWL appears most promising. The NRC should encourage the modeling and data user communities to prioritize the requirements and work with the DWL technologists and mission performance modelers.
- The advertised DWL velocity error is usually specified for the basic instrument performance. This instrument velocity error must be inserted into a velocity error budget that includes atmospheric effects (e.g., wind turbulence, wind shear), platform-induced errors (e.g., pointing and inaccurate inertial data), geometry, sampling, and other contributions to error. The final error to be compared to the requirement will be larger than the basic instrument error. The total wind velocity error, even with the excellent basic instrument error of the coherent DWL technique, may not meet the current strict requirements.
- Both DWL techniques suffer SNR loss as the inverse of the square of the range. Therefore the orbit height is a major factor to DWL. Mission designs for a NASA free flyer usually assume an orbit height of 400 km. However, the NPOESS satellites are planned for 833 km. This higher height reduces the SNR by more than 9 dB. Recent investigations into taking advantage of a possible opportunity to go to space on an NPOESS satellite have revealed that the loss of the 9 dB is much more detrimental to the direct DWL than to the coherent DWL. The aperture size of the direct DWL was driven up to 1.5 m, forcing a reliance on a very low TRL scanning technology. The laser size of the direct DWL was driven up forcing the lidar operation to reduce to 10% duty cycle for electrical power reasons while counting on the idea of adaptive targeting to provide science impact. Furthermore, accommodation of the direct DWL on the NPOESS satellite, having many other sensors on board, is doubtful. By contrast, the coherent DWL point design at 833 km featured 100% duty cycle operation and a 20 cm diameter telescope and scanner, which delivered excellent velocity accuracy about 20% of the time below 11 km. The optimum technology path to follow therefore depends on the orbit height choice. The NRC should encourage continuing interaction between the science community and the DWL technologists and mission performance modelers to resolve this issue.
- The problem of scanning a large aperture, which is needed for direct DWL, leads to two nontraditional concepts: 1) rotation of the entire spacecraft to effect a conical scan, and 2) formation flying and complementary pointing of several non-scanning DWL spacecraft. Since the DWL would have to be much larger without the assistance of step-stare scanning and shot accumulation, the first idea is not feasible. It also seems reasonable to dismiss the second idea as not affordable.
- The European Space Agency (ESA) is planning a launch of a direct DWL in 2008, called the Atmospheric Dynamics Mission (ADM). They are planning to have a 1.5 m diameter telescope mirror, and to only run the pulsed laser 25% of the time, cycling every 28 seconds[12]. They will not scan at all, and will therefore measure only a single line-of-sight

wind component, but not horizontal vector wind profiles. This mission will likely provide much interesting information on the direct DWL technology and technique, and on the atmosphere. But it will fall far short of even the "Threshold" requirements.

5 The Way Forward From Here

- The NRC should work to provide the information requested above on requirement priorities and orbit height to permit a more informed choice of the optimum "Horizontal Wind Profile" mission sequence that the US should undertake.
- We should pursue a "full court press" to develop the novel holographic scanner that is needed by direct DWL, to see if it can succeed in performing at large diameters up to 1.5 m, and with highly energetic 355 nm photons. The idea of simultaneous scanning of the 2-micron coherent DWL is also attractive, but secondary.
- Until the large direct DWL scanner is proven, mission designers should attempt to craft a hybrid concept that reduces the optical diameter of the direct DWL to the point that other scanner concepts, such as a rotating wedge or a rotating telescope, become feasible as back up approaches. This will, of course, be much harder at an 833 km orbit height.
- NASA's recent announcement of selecting two Instrument Incubator Program proposals to compactly package the coherent and direct DWL technologies should be augmented by continued development of the other technologies needed to address space accommodation issues and to ensure long term operation in space.
- Both coherent and direct DWLs should be flown together on a high altitude aircraft to permit investigation of the hybrid DWL concept in a downward looking geometry, and to validate ruggedness, autonomous operation, and performance predictions.
- A coherent DWL demonstrator space mission should be undertaken by the US. In view of the issues of orbit height, large scanner development, and accommodation faced by direct DWL, and since the ESA ADM mission will demonstrate non-scanning direct DWL, the US should demonstrate a scanning coherent DWL. Flight at 400 km is preferable, but an 833 km mission taking advantage of a free ride to space on an NPOESS satellite would still be a logical step.
- The US mission would not only demonstrate coherent DWL technology, technique, scanning, and vector wind profiles; but would gather essential information about the atmosphere to allow a re-examination of the wind measurement requirements necessary for justification of future missions. We anticipate that this will lead to a narrowing of the gap between the capabilities of direct and coherent DWLs, and "Significant" benefit to society.

6 Summary of the Mission Concept

The coherent DWL would use the pulsed 2-micron solid-state laser technology developed at NASA LaRC[13-19]. Compared to demonstrated pulse energies as high as 1.5 J, the laser would be operated at a derated pulse energy, perhaps 0.25-0.5 J, to extend laser life and to reduce demand on available mass and power resources. The laser pulse rate would be 10 Hz, yielding a transmitted optical power of 2.5-5 W. Current demonstrated laser wall plug efficiencies of 2% may be improved by as much as a factor of 2. The pulsed laser's electrical power requirement would therefore range from 62.5-250 W. The optical diameter of the telescope primary mirror would be approximately 0.2-0.5 m. The DWL would have a conical step-stare scanner, using a rotating optical wedge, which would be programmed to permit one or more parallel lines of horizontal vector wind profiles to be measured as the spacecraft advances. The conical scanner would permit forward and aft viewing directions to be paired to provide the equivalent of horizontal winds. The aft viewing laser shots would be placed as close as feasible to the previous forward viewing laser shots. The raw data would be downlinked to permit investigations into better data processing techniques leading to better wind velocity accuracy and measurement coverage.

The lowest cost to NASA would occur if the mission flies on an NPOESS satellite to 833 km orbit. A lower orbit height mission would permit either reduced instrument costs and risks, or greater coverage of the atmosphere.

The data product of this recommended mission will depend on the orbit height, laser pulse energy, the telescope diameter, and the number of horizontal vector wind lines to be measured. The data product will be horizontal vector wind profiles vs. height, with a basic instrument accuracy of approximately 1-2 m/s. Successful wind measurement will occur approximately 20-60% of the time from the surface to approximately 11 km. Above 11 km, the success percentage will fall, but occasional highly accurate measurements will occur.

7 Benefit to the Nation

This proposed mission will lead to a new operational capability that is highly desired and currently unmet.

A recent NASA NRA, Instrument Incubator Program-2004, lists the importance of the wind measurements to numerical weather prediction, hurricane tracking and landfall prediction, large-scale atmospheric transport, boundary layer dynamics, divergent flow component of the global atmospheric circulation, global energy cycle, and the atmospheric transport of water, energy, and chemical species. The NRA also refers to NASA's science focus area roadmaps. Of the 18 listed science focus areas, the wind measurement mission will make a primary contribution to 4 areas, and a secondary contribution to 11 other areas, for a total of 15 areas receiving a contribution. Table 4 shows this relevance. Note that CO_2 measurements can be made with the same lidar system at the same time as winds, aerosols, and clouds[20]. The wind measurement recommended here will also advance the identical laser and lidar technology needed for high-resolution, accurate, global CO_2 measurement.

8 Rough Estimate of Cost

This proposed mission cost to NASA will fall near the low end of the medium range category of $200-$500M, especially if NASA is not responsible for the spacecraft and rocket costs of an NPOESS launch. This estimate is based on NASA's experience with the GLAS and CALIPSO lidar missions.

Table 4. Contribution of a 2-micron coherent DWL mission to NASA's science focus areas

Science Focus Area	**Measurement Enabled By This Effort**	**Contribution**
Weather	Tropospheric Winds, Clouds, Aerosols	Primary
Disaster Management	Weather Forecasts (e.g., Hurricane Tracks)	Primary
Air Quality Management	Weather Forecasts, Aerosols, Winds	Primary
Aviation	Weather Forecasts, Winds	Primary
Climate, Variability and Change	Clouds, Aerosols, CO_2	Secondary
Atmospheric Composition	Aerosols	Secondary
Carbon Cycle, Ecosystems and Biogeochemistry	CO_2	Secondary
Water and Energy Cycles	Clouds, River Discharge	Secondary
Carbon Management	CO_2	Secondary
Coastal Management	Weather Forecasts, Winds	Secondary
Energy Management	Clouds, Aerosols, Weather Forecasts	Secondary
Homeland Security	Winds, Circulation Models	Secondary
Invasive Species	CO_2	Secondary
Public Health	Weather Forecasts	Secondary
Water Management	Weather Forecasts	Secondary

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