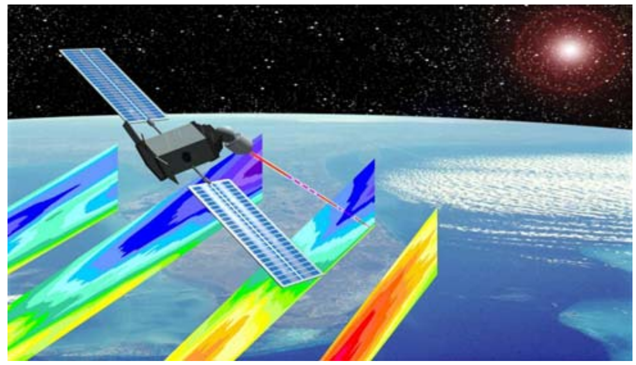
Providing Global Wind Profiles – The Missing Link in Today's Observing System

M. Hardesty (NOAA/ETL), W. Baker (NOAA/NWS), G. D. Emmitt, (SWA) B. Gentry (NASA/GSFC), I. Guch (NOAA/NESDIS), M. Kavaya (NASA/LaRC), S. Mango (NPOESS Integrated Program Office), K. Miller (Mitretek), G. Schwemmer (NASA/GSFC), J. Yoe (NOAA/NESDIS)

May 16, 2005

1. Needs and Benefits of Global Wind Profiles



A new satellite mission to accurately measure the three-dimensional global wind field is the final frontier that must be crossed to optimally specify global initial conditions for numerical weather forecasts. The wind field plays a unique dynamical role in forcing the mass field to adjust to it at all scales in the tropics, and at smaller scales in the extratropics[11]. Because of this, direct wind field measurement will have a much greater payback than improving accuracy and resolution of the mass field measurements already provided by advanced sounders, e.g. the Atmospheric Infrared Sounder (AIRS). A series of Observing System Simulation Experiments (OSSEs) carried out at Goddard Space Flight Center (GSFC), the National Centers for Environmental Prediction (NCEP), and the Forecast Systems Laboratory (FSL) have shown that accurately measuring the global wind field will have a major impact on numerical weather forecast skill at both regional and synoptic scales. Measurement of global wind profiles is recognized as the greatest unmet observational requirement for improving weather forecasts by the World Meteorological Organization, the large collection of nations planning the Global Earth Observation System of Systems, the National Polar-Orbiting Environmental Satellite System (NPOESS) Integrated Program Office (IPO), and NASA in its Weather Research Roadmap. Better wind measurements will directly support the missions of DoD, FAA, EPA, FEMA, DOT, DOE, USDA, and DHS.

Accurate measurement of the three-dimensional, global wind field will also allow major advances in our understanding of a host of key climate change issues. Common to many of these issues is the need for improved accuracy of horizontal and vertical transport estimates. Climate change issues that urgently need accurate global winds include: 1) improved knowledge of the vertical and horizontal transport of water vapor to verify the performance and integrity of climate models and to better understand the impact of deforestation on rainfall, 2) more accurate partitioning of the heat transport by oceanic and atmospheric components of the earth system, 3) improved understanding of the sources and sinks of the carbon cycle, which is currently based on the *a priori* specification of the wind field, and 4) improved understanding of long-range transport of aerosols and trace gases to assess the impact they may have on the regional and global climate.

In summary, the time is right for a national effort to develop a global wind measurement capability. Ironically, this effort has seemed to suffer in the past *because* of its broad benefit across a number of research programs and agencies – agencies have been hesitant to step forward and take the lead on a program that will substantially benefit other organizations. This paradigm can be changed by recognizing the impact of global wind measurements on the national interest, and bringing the agencies together to support a program to obtain these measurements.

2. How will global wind measurements be obtained?

Although several methods are currently available to observe winds in the atmosphere from space, all current techniques provide very limited vertical coverage. Active (e.g., scatterometer) and passive (e.g. radiometer) microwave techniques measure sea surface winds by measuring the intensity and asymmetry of microwave scatter or emission from the surface and converting this information to a wind signal. Although modeling techniques can be applied to infer winds at higher levels in the boundary layer from these observations, the actual wind measurements come from a single level. Similarly, tracking water vapor and cloud features in sequential images from geostationary or low earth orbiting satellites can under some conditions provide broad coverage of winds at a limited number of levels. These observations suffer from a lack of precise height assignment in addition to the limited height coverage.

For extended vertical observations of global wind profiles, active remote sensors with range resolving capability are required. Doppler lidar techniques, which measure the change in wavelength of radiation backscattered from atmospheric molecules and aerosol particles provide the best approach for full atmospheric coverage. No other viable alternative exists. Although Doppler radars can measure movement of cloud droplets and raindrops, only a small fraction of the volume in the troposphere and lower stratosphere contains clouds and rain at any given time. Molecules, however, are present in predictable amounts and aerosol particles abound in the boundary layer and clouds throughout the troposphere, providing a satellite-based lidar with continuous availability of scatterers.

2.1 Measurement requirements

Precision and resolution requirements for global wind measurements were developed at a Global Tropospheric Wind Sounder (GTWS) workshop for the research and operational communities. Briefly, the required measurements are global vertical profiles of horizontal wind vectors from 0 to 20 km altitude with horizontal resolution of 350 km along track, vertical resolution of 0.5 km in the boundary layer and 1 km in the free troposphere and stratosphere, and accuracy of ±2 m s^{-1} in the boundary layer and ± 3 m s^{-1} in the free troposphere.

The appropriate instrument for directly measuring global vertical wind profiles is a Doppler Wind Lidar (DWL) in a polar low earth orbit. This is especially true over the oceans. DWL measures line of sight wind velocity profiles using pulsed laser Doppler techniques. DWL observations are competitive with other observations and with the current models' first guesses, and are useful to both the operational and research communities.

2.2 A proposed measurement concept

Because Doppler lidars measure the component of the wind along the line-of-sight of the lidar, at least two observations from different pointing angles are required to resolve the horizontal winds in a target sample volume. Figure 2.1 shows a potential measurement concept for obtaining two dimensional wind vectors from space. As the spacecraft translates in orbit, a lidar beam is consecutively directed at a fixed nadir angle to each of 4 different azimuth angles in a conical step-stare arrangement. The scans are directed both fore and aft of the spacecraft to obtain two perspectives on the wind vector. At each location, backscattered return from range cells in the troposphere is averaged over several laser pulses to reduce measurement noise. Although tradeoffs between dwell time and measurement precision can be made, a typical measurement might include two measurements (four looks) made over a 350 km segment of the track, such that each look would be sampled for about 10 s, providing a local measurement over a sample volume of about 70 km.

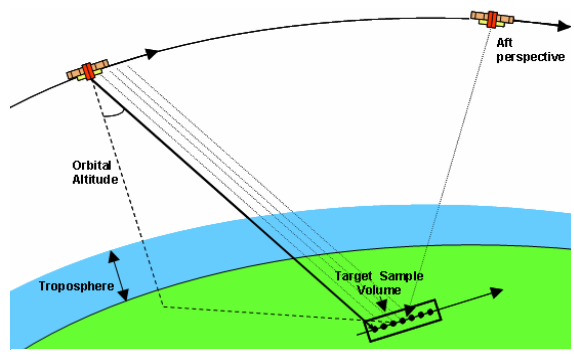


Figure 2.1: Winds measurement concept

2.3 Doppler lidar measurement techniques

Doppler lidars can measure winds by collecting the signal backscattered from atmospheric aerosol particles and/or molecules. Figure 2.2 shows a comparison of spectra for molecular and aerosol backscatter (for different transmitted wavelengths). At shorter wavelengths in the visible and UV, molecular scattering makes up a large part of the total scattering, while at longer wavelengths in the infrared (IR) aerosol scatter dominates. DWLs optimized for aerosol backscatter typically operate in the IR and use coherent Doppler lidar techniques[10], which are extremely sensitive for measuring the narrow-linewidth aerosol return. Coherent DWLs have been operated for more than 3 decades to measure 3-dimensional winds in field studies from a variety of terrestrial, ship and aircraft platforms. Coherent wind lidar systems do not measure winds from molecular

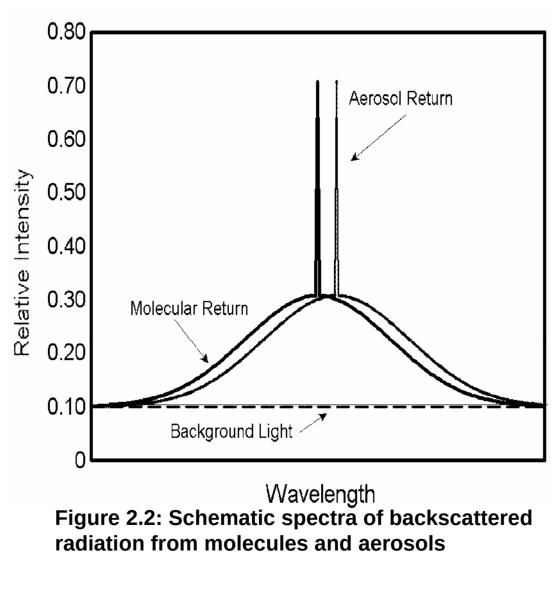


Figure 2.2: Schematic spectra of backscattered radiation from molecules and aerosols

backscatter return, but relatively small satellite-deployed systems could make measurements from high aerosol regions such as the boundary layer and from elevated cloud layers which are present over 70-80% of the globe.

Recently, direct detection DWLs have been demonstrated, employing interferometers to measure winds from both molecular and aerosol return. Direct detection DWLs can measure winds where atmospheric aerosol loading is minimal. A satellite direct detection system would most likely operate in the UV spectral region where molecular backscatter is highest. However, even though scattering cross-sections are high, the molecular backscatter bandwidth is so large (Fig. 2.2) that direct detection lidars must collect large numbers of backscattered photons to meet accuracy requirements. Thus high power lasers (tens of watts) and large collecting apertures (order of 1 m) are needed in space systems. Photon counts can also be increased by increasing collection time or range gate length, both of which degrade spatial resolution.

System studies have investigated both direct and coherent detection DWLs that could individually provide full vertical coverage at sufficient horizontal resolution. Both types of systems, if designed to provide full wind profiles, would require extremely large lasers and telescopes. For example, the European Atmospheric Dynamics Mission[13] (ADM), scheduled for launch in 2008, incorporates a UV direct detection DWL. The powerful laser (15 watts in the UV) and large telescope (1.5 m diameter) consume so much of the instrument weight and power budget that scanning has been dropped and only a single fixed perspective of the wind will be sampled. ADM provides one example of the tradeoffs faced in designing the instrument, where the trade space typically involves laser power, telescope size, single vs. bi-perspective wind measurement, and horizontal and vertical measurement resolution.

2.4 A proposed dual technology approach

Although ADM data will greatly benefit both instrument development and scientific efforts, we have concluded [9] that scientific impact is greatly increased when two perspectives of the wind are obtained, as shown in Figure 2.1. To obtain two perspectives, which will involve some form of scanning, and still keep the satellite to a reasonable size, we are investigating a concept that differs from ADM in two major ways. First, we suggest that a dual wavelength approach, incorporating both direct and coherent detection, would make best use of limited spacecraft resources. A moderately sized direct detection lidar would be designed to make measurements from molecular backscatter in the clear regions of the middle and upper troposphere and lower stratosphere. Because both precision and spatial resolution requirements in the upper troposphere are less demanding than in the lower atmosphere, the system could be considerably smaller than a direct detection instrument designed to provide the higher resolution measurements needed from lower heights. The direct detection system would be augmented by a small coherent lidar designed specifically for measurements in aerosol-enhanced regions such as the boundary layer and the ubiquitous cloud layers. Although technology to combine and scan laser beams for two subsystems in a single set of optics is challenging, the dual technology approach would provide an efficient use of spacecraft resources to obtain a high-impact science product.

Table 2. Nominal dual-technology parameters

Parameter	Coherent	Direct
Wavelength (microns)	2.05	355
Energy/pulse (Joules)	.250	0.2 @.355
PRF (design) (Hz)	10	100
Optical Efficiency (total)	.35	.3
Mixing Efficiency	0.42	N/A
Detector Efficiency	0.8	0.4
Collector Diameter (m)	0.5	.75 (HOE optional)
Integration Time (sec)	15	15
Wallplug Efficiency	0.035	0.06 (@ 1.064)
Weight	TBD	TBD
Power w/o scanner (watts)	62 (peak and average)	850 Peak (225 average)

The other major aspect of our satellite DWL concept, also aimed at optimizing system resources, is that the satellite be designed to operate in a targeted observations mode rather than a continuous sampling mode. Targeted observations save system resources to make intensive observations in those regions of each orbit where impact should be the greatest, such as around hurricanes, developing storms, etc., and turning the system off in other regions where the impact of wind measurements would be lower. In our concept, the direct detection molecular subsystem, which consumes the most power, will be operated in targeted observations mode, while the coherent aerosol system will provide winds from cloud layers and from within the boundary layer continuously. This approach recognizes that clouds are widespread over the earth's surface and that a coherent lidar can provide high resolution measurements from clouds and can also penetrate holes in cloud layers. Table 2 shows basic system parameters for a nominal dual-technology mission.

Significant work is underway to develop the technology and scientific underpinnings for an aerosol/molecular wind mission. The NASA Laser Risk Reduction Program (LRRP) is advancing laser capabilities at both UV and IR wavelengths to meet the specifications of a spaceborne hybrid DWL. NASA has recently funded two Instrument Incubator Proposals (IIPs) to develop airborne demonstration versions of the coherent and direct detection lidar subsystems that will comprise the dual technology mission. Also, NASA is investigating innovative ways to improve scanning technology, as is discussed in Section 6. The NPOESS IPO has funded ground and airborne DWL demonstrations, proof of concept activities, OSSEs, and calibration/validation activities. In parallel with technology development and demonstration, OSSEs are being carried out that show that a lidar operated in adaptive targeting mode should achieve a large portion of the benefits of a full 100% duty-cycle mission but require substantially less power and volume.

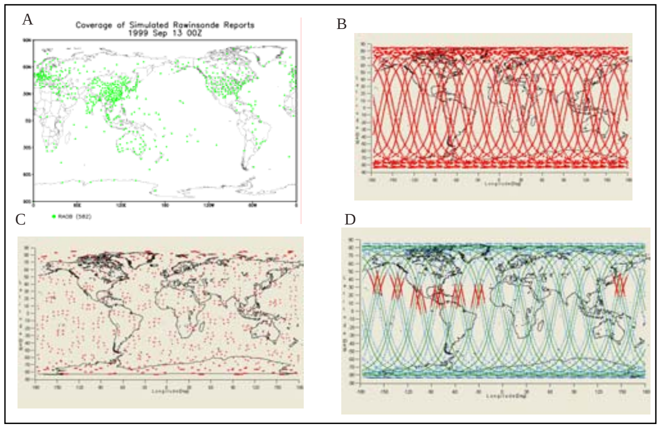


Figure 3.1 Comparison of global rawinsonde coverage (A) with PBL wind profiles from coherent subsystem (B), direct detection subsystem with random global 10% duty cycle (C) and full tropospheric soundings using CONUS focused adaptive targeting (D)

Instrument power, mass, volume, and scanning requirements suggest a free flyer mission in the lowest possible orbit, on the order of 400 km. However, we are also investigating an NPOESS Preplanned Product Improvement (P^3I) mission to demonstrate a DWL and operationally useful data with constrained space and power and in an 833 km orbit. The P^3I program provides a place on the NPOESS spacecraft and launch support for missions that provide or demonstrate new or improved critical environmental data products. Operation from an 833 km orbit may require a decreased duty cycle with targeted observations as well as some degradation of precision and resolution from those obtainable at 400 km.

3. What type of wind information will be provided by the satellite system and how will it be used?

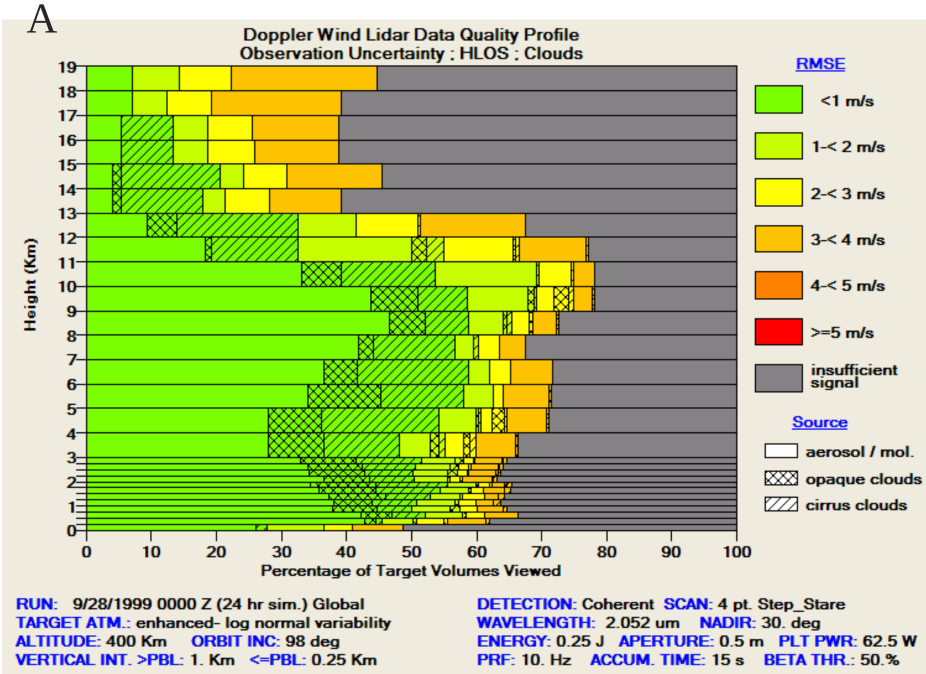
The envisioned operational space-based DWL will be in a 400 km polar orbit, making about 16 orbits per day with 900 potential LOS profiles per orbit within a 500 km swath. The vertical resolution will provide (clouds permitting) 22 levels of LOS wind observations. With scanning to acquire two perspectives, the global models will receive about 7200 horizontal wind vector profiles per day with quality better than rawinsondes. Most profiles will be over the oceans (see figure 3.1). The precision along the LOS would be ~1 ms^{-1} within the PBL and near cloud boundaries and ~ 2-3 ms^{-1} elsewhere. Depending on the scanning pattern and sampling rate of the lidar, the error of representativeness will be less than that of the rawinsonde but will still be the major contributor to the total observational error used in the data assimilation cost function.

The coverage of the wind profiles will depend on availability of aerosols and cloud coverage. Assuming that the lidar will penetrate cirrus clouds and be completely attenuated by non-cirrus clouds, the vertical coverage is expected to be close to that shown in figure 3.2. However, analyses of Lidar In-space Technology Experiment (LITE) data[8] and more recent data from the Geoscience Laser Altimeter System (GLAS) suggest nearly 50% "porosity" of all clouds to the narrow lidar beam. Thus, while the global cloud coverage is reported as being close to 80%, the lidar should penetrate to the ground ~ 60% of the time.

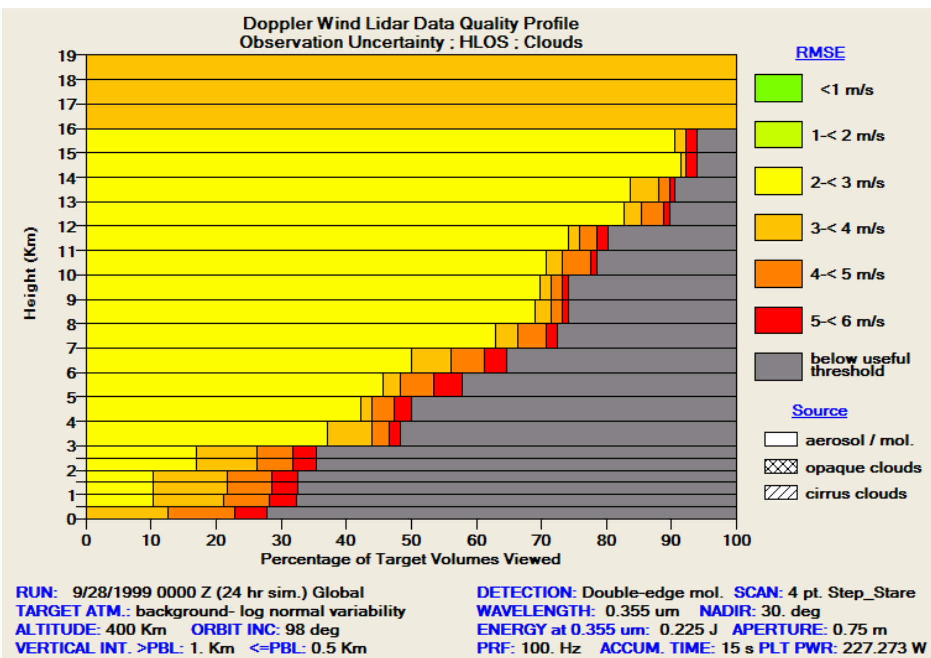
The issue of cloud effects on DWL coverage deserves additional discussion. To the first order, clouds represent both impediments to and sources for highly accurate direct wind measurements. While the lidar beam may penetrate cloudy layers and be attenuated by passing through them, the return from the cloud will be very strong and can be used as an independent wind observation and/or as a calibration point for Cloud Motion Vector observations currently being provided to the models. Although over most of the globe wind fields can be approximated using the quasi-geostrophic approximation, the ageostophic component of the wind is very critical to much of the mass and energy transport associated with the tropics, jet streams, and highly baroclinic regions. Perhaps the most promising aspect of DWL wind observations is the ability to measure the shear (frequently in multiple layers) within regions currently not sampled by rawinsondes.

Figure 3.2 Summary diagrams of vertical coverage (accuracy and source) for dual technologies (Table 2) in areas where observations are attempted. Note that coherent system (A) provides full soundings when aerosols are vertically pumped by convection. Direct detection (B) provides useful data even into the stratosphere when the system is energized (10% of time).

A



B



An additional feature of the DWL wind product is the ability to assign a quality factor to each observation based upon the number of photons detected and/or the level of local variability detected with multiple samples within a small volume. The overall utility of the DWL data for assimilation is greatly enhanced by the individual observation quality flag.

4. What is the anticipated impact of global wind profiles on operational capability and Earth Science needs?
Some specific benefits of direct global wind profiles are listed in the following:

Benefits to government, industry, and academia	Benefits to military missions
• Atmospheric and climate science, e.g. transport of moisture, pollution, CO2 sources and sinks • Ecosystem impacts via droughts, productivity, fire • Meteorological data for survivability of species • Weather and air quality forecasting • Extreme weather forecasting (e.g. hurricane) • Military and civilian aircraft and shipping operations • Agriculture (rainfall, frost, temperature) • Construction • Energy infrastructure demand and risk forecasts • Homeland security	• Space Launch • Flight Planning/Aviation Ops • Dispersion Forecasts for NBC Releases • Precision Weapons Delivery/Strike Option Planning • Precision Airdrop • Reconnaissance • Aerial Refueling • Artillery • Battle Space Awareness

Since we do not have global wind soundings from space, the DWL community has employed OSSEs to explore their effects. These model-based experiments address key issues: how best to distribute observations, trades between accuracy per observation vs. number of observations, and coverage (vertical and horizontal) vs. forecast skill. OSSEs have assessed potential impacts on analyses and forecasts on both the global and regional scales. OSSEs, funded by NASA and NOAA, have consistently revealed DWL impacts judged to be extremely significant compared to what is possible with existing observing systems. Most recently, the benefits of adaptive targeting observations have been explored (figure 4).

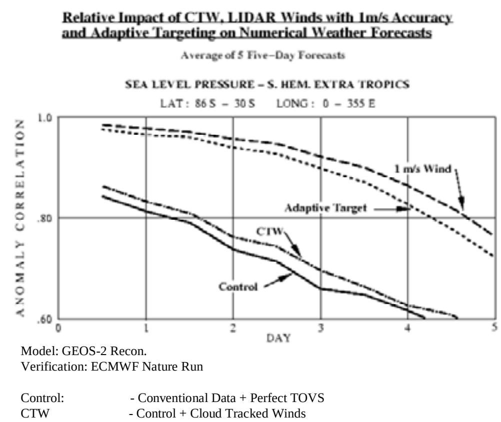


Figure 4. Experiments conducted at GSFC suggest that 90% of the DWL data impact on sea level pressure forecast results from just 10% of the data that can identified in the analyses fields.

While most early OSSEs addressed global scale impacts of a space-based DWL, attention has recently shifted to study of the impacts on specific weather phenomena having mesoscale dimensions (e.g. hurricanes, winter storms, jet steaks, etc.). NOAA FSL conducted OSSEs using the MM5 and the RUC-2 models that revealed much larger impacts within the model domain than had been anticipated. GSFC experiments show very significant improvement in hurricane track predictions when DWL profiles are included. Potential savings from improved hurricane and storm track warnings are immense. Over the past 20 years, nine hurricanes have exceeded $5 billion per storm in damages, and cost hundreds of lives. Savings can result from reduction of preventable property damage and reduction of over-warnings that cause unneeded preparation and evacuation. Total savings from improved hurricane warnings have been estimated at over $200 million each year.

George Washington University studies[7] estimated benefits and costs of a space-based DWL. The results showed that a ½ % improvement in the prediction of the winds would result in hundreds of millions of dollars in annual fuel savings by civilian (over $130 million) and military (over $15 million) aviation that would easily cover the cost of a DWL in space. When the "cost avoidance" savings in unnecessary storm preparations and evacuations are added in, the cost benefit ratio easily exceeds 1:3, assuming a mission cost of several $100 million.

5. Doppler Wind Mission Elements and Costs[1]
Major elements for a global winds mission include DWL instrument development, spacecraft integration, launch, and operations. These elements were analyzed by GSFC rapid design teams[2] in 2001-02. Since that time, the

mission concept has advanced to a dual technology DWL on a free flyer platform in a 400 km polar orbit. The dual technology instrument is expected to reduce overall costs and shorten the instrument development timeline. An alternative NPOESS P^3I mission is also being studied.

Instrument: The major concerns identified by GSFC rapid design were instrument power (including large solar array and radiator size), mass, volume, lasers (power, efficiency, and lifetime), and scan system. These concerns pointed to the need for advances in lasers, detectors, low mass telescopes, and scanners. Importantly, a new hybrid instrument point design[3] and studies of adaptive targeting[6] have significantly reduced all of these concerns. Subsequent technology development[3,4,5] has advanced component technologies. Required instrument activities include:

- Laser, detector, telescope, scanning, and pointing component development to attain performance, technology readiness, lifetime validation
- Ground and airborne testing to prove performance and reduce risk
- Space qualification and packaging

Spacecraft: Available spacecraft technology can accommodate this mission. Momentum compensation and pointing accuracy are critical.

Launch: Studies at the Goddard Integrated Mission Design Center (IMDC) showed that instrument size and mass are within the capabilities of a Delta class (3 meter fairing) launch vehicle[2]. The direct detection subsystem telescope is the largest component. The hybrid design could enable use of a smaller launch vehicle.

Operations: The first space mission will provide operationally useful data as well as technology demonstration. Communications requirements can be met with available capabilities. Data assimilation has been demonstrated in OSSEs at the NASA/NOAA/DoD Joint Center for Satellite Data Assimilation (JCSDA).

Cost: The estimated cost is in the medium-size mission category ($200 M to $500 M) to complete component research, develop and test the instrument, integrate the spacecraft, launch and operate a space mission.

6. How ready are we for a mission?

The key lidar technologies- solid state lasers, large aperture telescopes, efficient photon detectors- have steadily matured to the point where space based lidar systems have crossed the readiness threshold, becoming operational instruments with unique capabilities to observe surface and atmospheric properties in three dimensions. Today, NASA has three lidar systems in space: the Mars Orbiting Laser Altimeter (MOLA); the Geoscience Laser Altimeter System (GLAS); and the Mercury Laser Altimeter (MLA). A fourth lidar, CALIPSO, will be launched in June, 2005. Each successive lidar mission has demonstrated improved capabilities based on an expanded base of available technologies.

Future global wind systems will build on this space lidar heritage but require additional advances to meet the specific needs of the Doppler lidar wind measurement. For example, the precise nature of the Doppler frequency shift measurement requires that laser transmitter spectral properties (e.g. center wavelength, spectral linewidth) need to be well defined. The requirement for horizontal wind vector measurement requires lidar line-of-sight wind speed from multiple perspectives using an off-nadir pointing telescope. The multiple-perspective requirement implies either multiple telescopes or azimuthally scanned optics. There are additional technology challenges in DWL receivers, in precise pointing knowledge and control, and in motion compensation to correct for the >7.5 km/sec spacecraft velocity.

Finally, as noted above, meeting wind measurement requirements with either a standalone molecular direct detection DWL or a standalone coherent DWL inevitably leads to laser power and telescope/scanner aperture requirements an order of magnitude beyond current capabilities. Recent studies indicate that a dual wavelength lidar combining a direct detection channel sensing molecular motion with a coherent detection channel sensing aerosol and cloud motion will help mitigate the large power and aperture requirements. Many of the technology challenges remain the same but the scale of the technology gap is greatly reduced by using smaller lasers and telescope scanner optics that are closer to those available today. The additional benefit of a dual wavelength approach is a great reduction in spacecraft power and mass requirements, making a mission more affordable in the near term.

A number of current technology development programs are addressing the DWL technology gaps. Programs funded by NASA, NOAA, and industry are developing component technologies (e.g. detectors, HOE, pump diode arrays) and lidar subsystems (e.g. 1 and 2 micron pulsed lasers, local oscillators and Doppler receivers). Specific investments range from NASA Small Business Innovative Research (SBIR) programs to the NASA LRRP, an ambitious multi-year program addressing many key problem areas unique to spaceflight qualified lasers. Industry programs are also advancing key lidar subsystems. Finally, several integrated DWL development and demonstration programs are ongoing, including two NASA IIP projects and the NOAA-sponsored BalloonWinds program. These projects represent system level demonstrations of key component technologies and subsystems from relevant ground, aircraft, or balloon platforms and will push the Technology Readiness Levels (TRLs) of many technologies to level 5 or 6.

DWL demonstrations on the ground and in aircraft are significant milestones on the path to space. However, operation from space differs in several ways, including greater range from DWL to target, large platform velocities requiring Doppler motion compensation, scanning a large telescope on a spacecraft, spacecraft environmental factors, and autonomous operation. Preparation for a space mission requires adaptation to these differences. Finally, for the hybrid DWL approach there is the potential technology synergy of utilizing a common telescope/scanner subsystem based on holographic optical element (HOE) or diffractive optical element (DOE) technology. With adequate funding, the longer lead advances are attainable in three years. In the paragraphs below, the TRLs of key DWL and scanning optics components and subsystems will be discussed.

6.1. Direct Detection Subsystem[12]

Table 6.1 shows TRLs of key components of the Direct Detection Subsystem of a dual wavelength DWL. Current direct detection technology development activities include several NASA SBIR programs, the NASA LRRP, the NOAA BalloonWinds and GroundWinds programs and the NASA Tropospheric Wind Lidar Technology Experiment (TWiLiTE) IIP project. The laser transmitter targets (Nd:YAG assumed) are 320 mJ at 50 Hz PRF, line width < 100 MHz, wall plug efficiency 2.5%, lifetime 3 years, and conductive cooling. Other Nd:YAG space lasers include MOLA, GLAS, CALIPSO and MLA. Single frequency operation of the pulsed laser requires a very stable, continuous wave seed laser to seed the pulsed laser cavity. The seed laser needs a lifetime rating of 3 years.

Table 6.1. Direct Detection Component TRLs

Direct Detection Component	TRL	Current Activities	TRL after Current Activities
Pulsed 1064 nm Nd:YAG Laser frequency tripled to 355 nm	4	Industry IRAD, NASA LRRP, IIP, BalloonWinds	6
Seed laser	8	AURA TES	8
High resolution Fabry Perot filter	4	SBIR, IIP, BalloonWinds GroundWinds	6
355 nm detector, PMT	5	NASA GLOW, IIP	5
355 nm detector, CCD	3	BalloonWinds GroundWinds ADM	5
Molecular Doppler receiver	4	NASA GLOW, IIP, BalloonWinds GroundWinds	6
Scanning Telescope (Rotating HOE)	3	SBIR, NASA IIP	5
End-to end optical efficiency	3	NASA GLOW, IIP, BalloonWinds GroundWinds	5

Two candidate direct detection DWL receiver designs have been demonstrated at GSFC and in GroundWinds. Both receivers are based on high spectral resolution tunable Fabry Perot interferometers. Target receiver technology advances are spaceflight qualified Fabry Perot interferometers and detector improvements. Candidate detector technologies and performance objectives are 35% detector quantum efficiency for single photon counting photomultiplier tubes and 80% quantum efficiency for CCD imaging detectors. Additional receiver developments are sought to improve end-to-end receiver optical efficiency to 10%. Baseline designs for a 1 meter class rotating telescope, operating at a 45 degree nadir angle have been proposed. This is consistent in size with the all beryllium 1 meter telescopes flown on GLAS and CALIPSO indicating the TRL might be quite high for the telescope. However, the added complication of pointing off nadir and rotating the large mass to achieve multiple perspectives make alternative approaches such as the holographic optical element attractive.

A top level summary of current TRLs for key direct detection sub-systems is in column 2 of Table 6.1. Columns 3 and 4 show development activity and expected TRLs at the conclusion of the activities.

6.2. Coherent Detection Subsystem

Table 6.2 shows TRLs of key components of the Coherent Subsystem of a dual wavelength DWL. This subsystem is based on a pulsed, solid state 2 micron laser. The 2 micron laser is being developed for space based operation at NASA Langley Research Center (LaRC) as part of the LRRP. The coherent lidar requires a frequency agile 2 micron local oscillator laser. The telescope for the coherent-only subsystem can utilize a rotating optical wedge scanner, developed and qualified for space operation as part of the Space Readiness Coherent Lidar Experiment (SPARCLE). Alternative designs utilizing HOE or DOE technologies are at lower TRL but could be used in a dual wavelength DWL. The room temperature 2 micron detector and integrated heterodyne receiver technologies are also being developed as part of the LRRP. System level demonstration of the 2 micron technologies is ongoing at LaRC in the ground-based Validar system and in airborne systems such as Twin Otter DWL (TOWDL), a system developed with Navy and IPO funding and also in systems developed at NOAA ETL. The 2 micron lidar technology will be further advanced in recently selected IIP activities.

Table 6.2. Coherent Detection Component TRLs

Coherent Doppler Lidar for Space	TRL	Current Activities	TRL after Current Activities
Pulsed 2 Micron Laser	3-4	LRRP IIP	4 except Lifetime=3
Detector, 2 Micron, Room Temperature	5	LRRP	5
Telescope	4		4
Scanner, Rotating Wedge	6		6
Pointing	7		7
Autonomous Operation	2-5	CTI	2-5
Pre-Launch Lidar Photon Sensitivity Validation	3	From SPARCLE	3
Pointing, Nadir Compensation	2-7		2-7
Compensation Optics for Nadir Angle Tipping	2		2
Detector for Alignment Maintenance	2	U of CO	2
Space Environmental	2	LRRP	2

6.3 Scanning telescope for dual wavelength DWL

The scanning telescope is a critical space system element because of its mass, volume, and power requirements. Although GSFC Instrument Synthesis and Analysis Laboratory (ISAL) and IMDC studies showed feasibility of conventional optics, two new approaches promise to significantly reduce mass and power. They are the Rotating Holographic Optical Element (RHOE) and the Shared Aperture Diffractive Optical Element (ShADOE).

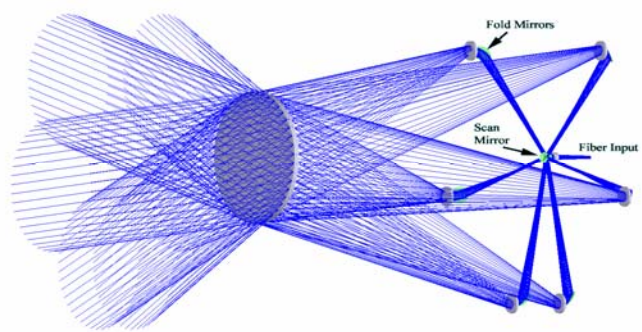


Figure 6. Ray tracings for a ShADOE with six exposures, each oriented so the collimated portion is directed toward a central rotating scan mirror that sequentially addresses each FOV, directing the light to a single optical fiber.

RHOE. NASA has been developing RHOE scanning telescope technology for several years. Successful air and ground direct detection lidar demonstrations show reliable conical scanning with single RHOEs for 532nm and 1064nm wavelengths. Performance is equal to or better than conventional reflective lidar telescopes, and the mass, volume, and power savings are substantiated. Recent lab tests show that the same functions can be performed at 355 nm (UV), and work is in progress to bring this technology to TRL 4. Scaling up to 1-meter size and space-qualifying materials remain to prepare for a spaceborne direct detection DWL. The 2001 ISAL study recommended an RHOE for a free-flyer DWL over conventional optics. But the mass, power, and momentum compensation for an RHOE are still large cost drivers for a space mission, since rotating a flat 1 to 2 meter diameter disk in a step-stare manner remains an engineering challenge.

ShADOE. The new ShADOE technology promises to remove all large moving components, providing significant weight, power, and momentum compensation savings. ShADOE incorporates several independent HOE telescope primaries into a single holographic film, each with a separate field of view and focal plane. These are addressed sequentially with a small focal plane scan mirror or a fiber-switching network. The IR aperture for coherent detection is roughly 1/3rd the diameter of the UV aperture. One concept for combining the two is to make a single optic where the central portion is used by IR and the outer annulus by UV holograms. The optical paths for a single wavelength 6-telescope ShADOE are shown in Figure 6.

Optics TRLs. Scanning Telescope TRLs are shown in Table 6.3. Current activities are supported by the NASA IIP, SBIR program, and Advanced Components Technologies (ACT) programs and NPOESS Integrated Program Office Risk Reduction (IPORR). The ACT activities in parentheses are proposed activities. Estimated years to attain the new TRL are in parentheses in the last column.

Table 6.3. Scanning Telescope TRLs

Scanning Telescope	Current TRL	Current (& Proposed) Activities	TRL after IIP	TRL after Current (& Proposed) Activities
355 nm RHOE	3	IIP, IPORR	6	6
355 nm ShADOE	3	IIP, (ACT)	3	5 (2007)
2054 nm Wavefront Correction	2	IPORR, SBIR, (ACT)	N/A	5 (2006)
2054 nm ShADOE	2	IPORR, SBIR, (ACT)	N/A	5 (2007)
Dual Wavelength ShADOE / Scanner	2	IPORR, SBIR, (ACT)	N/A	5 (2008)

For direct detection, ShADOE technology is at TRL 3. Coherent detection requires two advances: operation at 2054 nm, and diffraction-limited optical performance. Both are being addressed. With sufficient funding, this technology could be advanced from TRL 2 to TRL 6 in approximately 3 years. RHOE for 355 nm direct detection is at TRL 4. Since it was demonstrated at 1064 nm in an airborne lidar, it should rapidly move to TRL 6 from IPO, GSFC R&TD, TWiLiTE IIP funding. Materials need to be space qualified early in the process since the technology is very material dependent. We recommend additional investment in space qualification work now so that both concepts can rapidly advance to TRL 7 & 8.

7. How do we proceed to implement the mission?

Figure 7 diagrams activities to achieve a wind mission. A combination of government, private sector, and academic support is needed. A Data Requirements Review is needed to reassess the sensitivity of benefits to data requirements. Recent studies[6] suggest that GTWS threshold requirements can be relaxed without significant loss of benefits. This can reduce time and cost to a successful mission. Instrument and mission architecture alternatives should be compared and an architecture baselined.

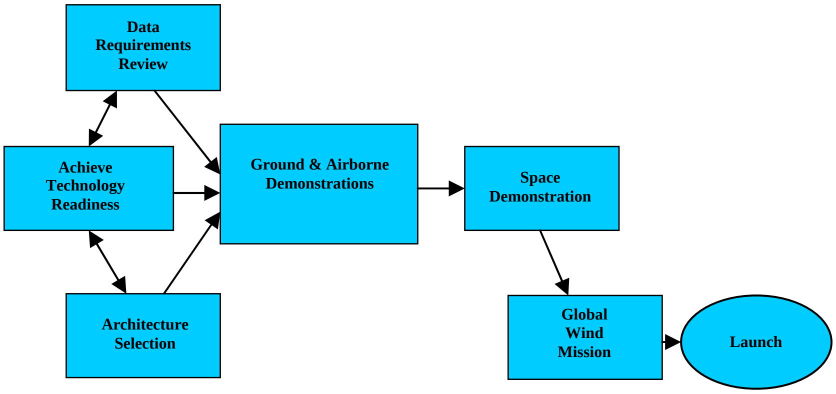


Figure 7. Activities leading to a DWL mission

The Achieve Technology Readiness activity will continue to advance component and integrated instrument TRLs as discussed above. Lasers, detectors, and scanning telescopes still have longer lead times and need high priority. Ground, airborne, and space demonstrations are needed to advance the instrument TRLs and reduce risk. A space demonstration should demonstrate technical capability and usefulness of winds data from space. Demonstration on an NPOESS P^3I mission is being considered. Other alternatives are the shuttle, the International Space Station, a DoD Space Test Program mission, or other platform. The Operational Mission will acquire, launch, and operate the instrument and spacecraft, communications, operations center, data production facility, and produce and distribute data products.

8. Summary

Global winds observations are a vital national need promising an excellent benefits/cost ratio. A dual wavelength DWL with advanced scanning optics offers a promising instrument approach for the near term. The enabling technologies are advancing, and high priority support is recommended to advance the component technologies, conduct ground, air, and space demonstrations, and achieve a full global wind mission.

References

1. Miller, K., et al, (2004), *Technology Roadmap for Deploying Operational Wind Lidar*
2. Instrument Simulation and Analysis Laboratory (ISAL) and Integrated Mission Design Center(IMDC), (2001-02), NASA GSFC
3. Emmitt, G. D., (2004), IPO Hybrid DWL Point Design
4. NASA Laser Risk Reduction Program (LRRP),(2003)
5. NOAA/University of New Hampshire GroundWinds and BalloonWinds DWL Programs.
6. Atlas, R. and Emmitt, G. D., (2005), OSSEs and findings on adaptive targeting.
7. Cordes, J. (1995, 1998), *Economic Benefits and Costs of Developing and Deploying a Space-Based Wind Lidar* and *Projected Benefits in Military Fuel Savings from Lidar*, GWU
8. Winker, D., G. D. Emmitt, (1997), *Relevance of Cloud Statistics Derived from LITE Data to Future Doppler Wind Lidar*, 9th Conf on Coherent Laser Radar, Linkoping, Sweden
9. Riishojgaard, L. P., R. Atlas and G. D. Emmitt, *The Impact of Doppler Wind Observations on A Single-Level Meteorological Analysis*, J. Applied Met, 43, 810-820
10. Huffaker, R. M. and Hardesty, (1996), *Remote Sensing of Atmospheric Wind Velocities Using Solid-State And CO2 Coherent Laser Systems,* Proceedings of the IEEE
11. Baker, W. et al, (1995), *Lidar-Measured Winds from Space: A Key Component for Weather And Climate Prediction*, Bulletin of the American Meteorological Society, volume 76
12. Gentry, B. M. et al, (2000), *Wind Measurements with A 355 nm Molecular Doppler Lidar*, Optics letters, volume 25
13. Flamant, P. et al, (2005), *The Atmospheric Dynamics Mission for Global Wind Field Measurement*, Bulletin of the American Meteorological Society, volume 86

Acknowledgment

The support of the NOAA/Integrated Program Office is sincerely acknowledged, especially that of Dr. Stephen Mango.