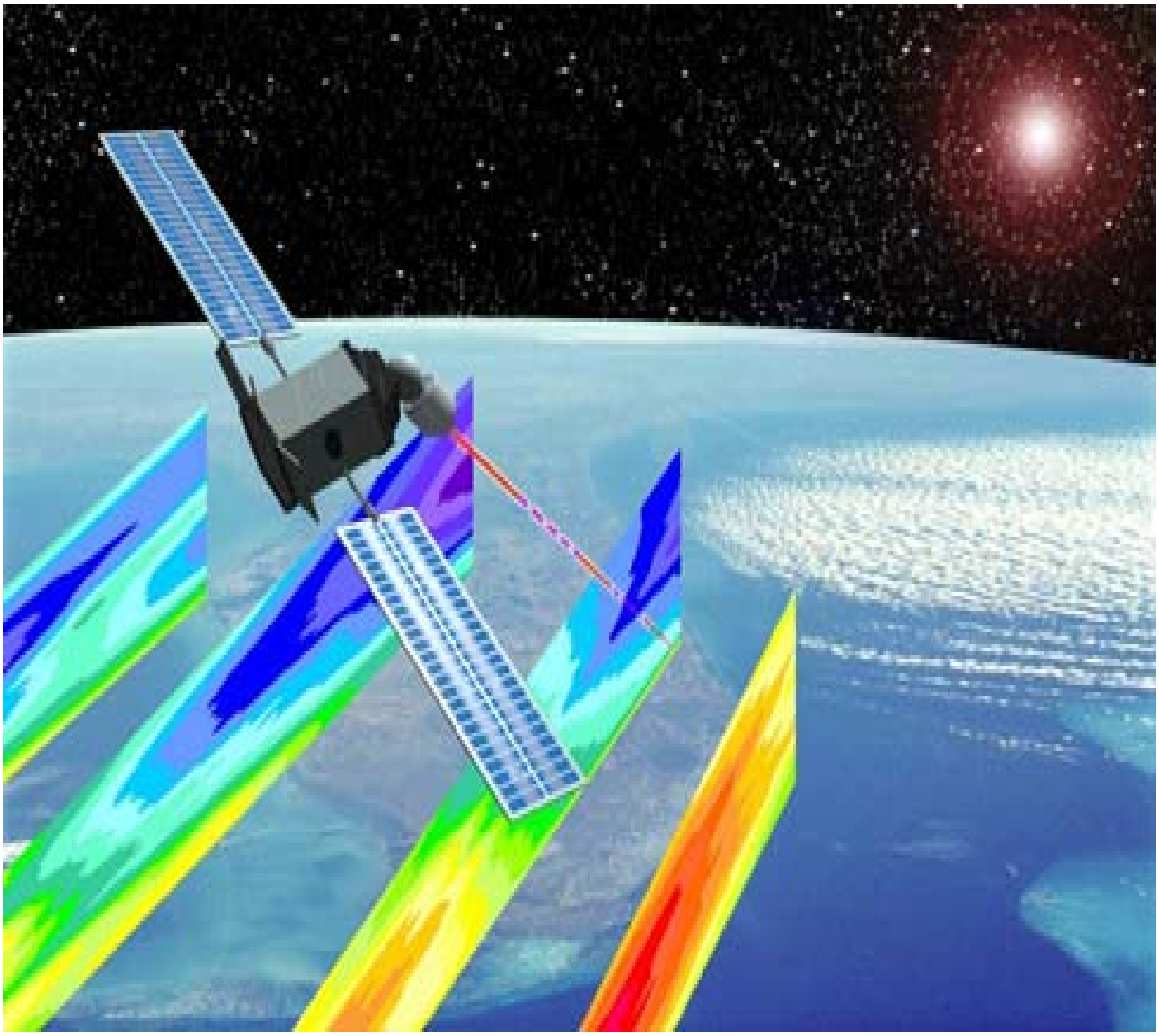
Wind Profiles – The Missing Link in the Global Observing System



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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 small scales in the extratropics[11]. Because of this, direct wind field measurement will have a much greater payback than improving the 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 Environmental Systems Research Laboratory (ESRL) show that accurately measuring the global wind field will have a major impact on numerical weather forecast skill at both regional and synoptic scales. Recent forecast impact experiments with actual measurements, obtained with an airborne Doppler Wind Lidar (DWL) and assimilated into the European Centre for Medium-Range Weather Forecasts (ECMWF) global model, confirm the OSSE predictions (see Fig. 1.1 below[15]). On the average, the DWL data reduced the 48 h 500 hPa forecast error by ~ 0.5 m (3%) and the 72 h error by ~ 1 m (3.5%). For comparison, the typical reduction in the 72 h 500 hPa forecast error at the operational numerical weather prediction centers worldwide has been ~ 10 m in the past 10 years, as a result of all of the improvements in modeling, observing systems, and computing power. In addition, in the study noted above, the DWL data were found to have roughly a 40% larger influence on the analysis than dropwindsonde data, and the total information content of the DWL measurements is about three times higher.

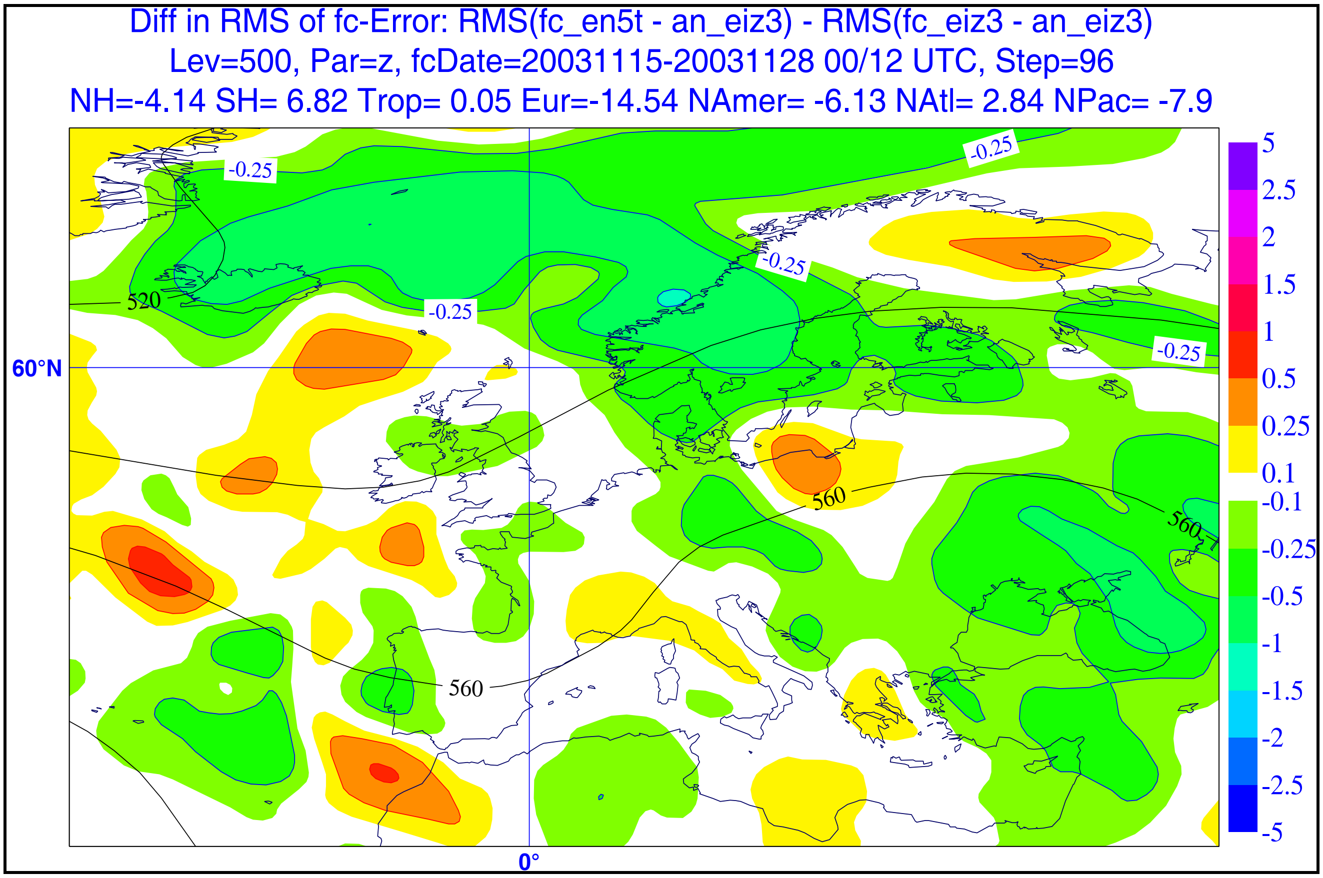


Fig. 1.1 Mean (29 cases) 96 h 500 hPa height forecast error difference (Lidar Experiment minus Control Experiment) for 15 - 28 November 2003 with airborne DWL data[15]. The green shading means a reduction in the error with the Lidar data compared to the Control. The forecast impact test was performed with the ECMWF global model.

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. Moreover, "Wind profiles at all levels" is listed as the number one priority in the strategic plan for the United States Integrated Earth Observing System (USIEOS).[14] Also, the measurement of "wind speed and direction" is stated as having a "high level of importance" in five of nine societal benefit areas in the USIEOS. Global wind profiles will directly support the missions of NOAA, NASA, 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. 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 gas forcing.[20,21,22,23] 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. Given these limitations, it is unclear whether we have the ability to detect decadal timescale changes in the atmospheric circulation (possibly forced by human activity) even if they are already underway. Furthermore, other research has shown that cloud fields are strongly influenced by the circulation,[18] and hence circulation changes and their influence on clouds may contribute to the large uncertainty in the sensitivity of the climate to greenhouse gas forcing.[19] Accurate measurement of the three-dimensional, global wind field is essential to test these ideas.

In addition to these questions of climate sensitivity, there is also a need for improved accuracy of horizontal and vertical transport estimates for climate applications. Climate change issues that would significantly benefit from 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, better understand the impact of deforestation and other human activities on rainfall, and better understand the processes that control water vapor in the upper troposphere and lower stratosphere, 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, 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, and 5) improved re-analysis data sets to provide a more accurate environmental data record for climate studies.

2. What is the Anticipated Impact on Operational Capability and Earth Science Needs?

Some specific benefits from global wind profiles from a space-based DWL are listed in Table 2.1.

Table 2.1 Specific benefits from wind profiles from space.

Government, Industry, and Academia	Military Missions
Atmospheric and climate science, e.g. transport of moisture, pollution, CO2 sources and sinks	Space launch
Flight planning, aviation operations, and turbulence	Flight planning, aviation operations, and turbulence
Dispersion forecasts for nuclear, biological, chemical releases	Dispersion forecasts for nuclear, biological, chemical releases
Ecosystem impacts via droughts, productivity, fire	Precision weapons delivery/ strike option planning
Meteorological data for survivability of species	Precision airdrop
Weather and air quality forecasting	Reconnaissance
Extreme weather forecasting (e.g. hurricanes)	Aerial refueling
Aircraft and shipping operations	Artillery
Agriculture (rainfall, frost, temperature)	Battle space awareness
Construction	
Energy infrastructure demand and risk forecasts	
Homeland security	

The following examples illustrate the magnitude of the potential benefits to the Nation's economy from a space-based DWL. Over the past 20 years, nine hurricanes have exceeded $5 billion per storm in damages, and cost hundreds of lives (the devastating 2005 hurricane season statistics are not included). 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[7] studied the benefits and costs of a space-based DWL and found that even with a very modest 0.5% improvement in the accuracy in the wind forecast, substantial annual fuel savings would result for civilian (over $130 million) and military (over $15 million) aviation. This amount would easily cover the cost of developing, launching and operating a space-based DWL. When the "cost avoidance" savings in unnecessary hurricane storm preparations and evacuations are included, the benefit-cost ratio easily exceeds 3:1 over the life of the mission, assuming the cost for demonstration and operational missions of several $100 million (see Section 7). Note that these benefit-cost studies used estimates of fuel and evacuation costs from the 1990s. Using current costs would substantially increase the benefit-cost ratio.

3. How will Global Wind Measurements be Obtained?

Although several methods are currently available to observe winds 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 estimate. 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 for observation using satellite-based lidar.

Analyses of data from lidars in space (LITE and GLAS) reveal that although 75 – 80% of the individual lidar shots intercept cloud, ~ 60% of those shots also provide a ground return. Thus, the overall laser beam penetration to the earth's surface is ~ 70%. This cloud porosity is far greater than a global cloud coverage figure of 75% would imply, and, thus, full tropospheric wind profiling will be the rule rather than the exception.

3.1 Measurement requirements

Accuracy and resolution requirements for global wind measurements were developed at a joint NOAA/NASA Global Tropospheric Wind Sounder (GTWS) workshop for the research and operational communities in 2001. Briefly, the GTWS Workshop participants determined that 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 $\pm 2\ ms^{-1}$ in the boundary layer and $\pm 3\ ms^{-1}$ in the free troposphere.

The appropriate instrument for directly measuring global vertical wind profiles is a DWL in a polar low earth orbit. A 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.

3.2 *Satellite lidar 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 3.1 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 target sample volume from two different perspectives. The lidar has a fixed nadir angle and uses a conical step-stare scanning arrangement. The scans are alternatively directed fore and aft of the spacecraft to obtain the two perspectives on the wind vector. At the location of each target sample volume, backscattered return from range-gated cells in the troposphere is averaged over several laser pulses to reduce measurement noise. Multiple lines of measurements are made across the satellite's ground track. Although tradeoffs between dwell time and precision can be made, a typical measurement might include bi-perspective sampling of two lines (four looks) or four lines (8 looks) across each 350 km segment of the satellite ground track. Each look would be sampled for 5 to 10 s, providing a local measurement over a sample volume of about 70 km. Note, the time difference between the fore and aft shots is ~ 1 min and several 10s of meters, which is small compared to the scales of the wind field changes being sampled.

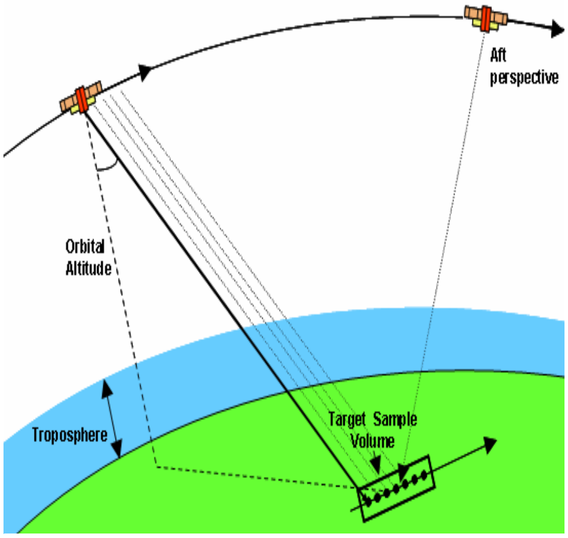
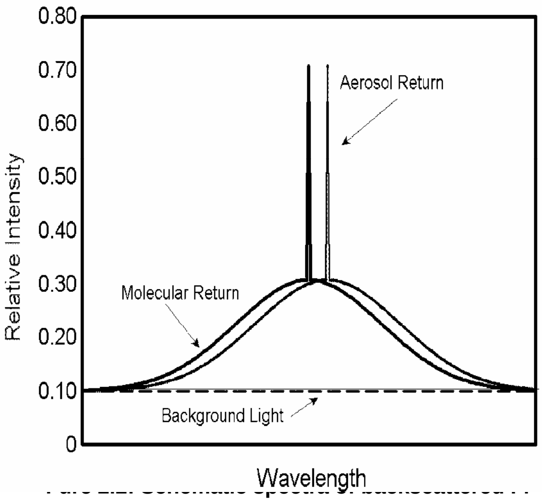


Fig. 3.1 Wind measurement concept

3.3 *Doppler lidar measurement techniques*

Doppler lidars measure winds by collecting the signal backscattered from atmospheric aerosol particles and/or molecules. Figure 3.2 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. At longer wavelengths in the infrared (IR), aerosol scatter dominates. DWLs optimized for aerosol backscatter typically operate in the IR and use coherent detection techniques[10] which are extremely sensitive for measuring the narrow line width aerosol return. Coherent DWLs have been operated for more than three decades to measure three-dimensional winds in field studies from a variety of terrestrial, ship and aircraft platforms. Coherent wind lidar systems do not measure molecular backscatter



3.2 Schematic spectra of backscattered radiation from molecules and aerosols

return. Relatively small satellite-deployed coherent detection lidars 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.

More 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 or absent. A satellite direct detection lidar would most likely operate in the UV spectral region where molecular backscatter is highest. However, the molecular backscatter bandwidth is so large (Figure 3.2) that direct detection lidars must collect large numbers of backscattered photons to meet wind 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 improved 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 that meet GTWS requirements. 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 late 2008, incorporates a UV direct detection DWL. A 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 (line of sight) perspective 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 resolution.

3.4 A proposed approach for satellite wind measurements

Although ADM data will greatly benefit both instrument development and scientific efforts, we have concluded[9] that the scientific impact will be greatly enhanced when two perspectives of the wind are obtained, as shown in Figure 3.1. 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 important ways. First, we are pursuing a hybrid DWL approach, incorporating both direct and coherent detection, which would make the 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 accuracy 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 at lower altitudes. 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. 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. The hybrid approach will provide an efficient use of spacecraft resources to obtain a high-impact science product. Table 3.1 shows the basic system parameters for a nominal hybrid DWL mission.

The other important difference with ADM is also aimed at optimizing system resources by operating the direct detection component of the hybrid DWL in a targeted observations mode rather than a continuous sampling mode. Targeted observations could save system resources if intensive observations are made in those regions of each orbit where the impact should be the greatest, using the spread of ensemble forecasts to select target regions. The geographical coordinates of regions that are upstream of the ensemble forecast spread could be up-linked to the satellite for phenomena such as hurricanes, developing storms, etc. The system would be turned off in regions where wind measurements are expected to have little impact on the forecasts. The direct detection molecular system, which consumes the most power, would be operated in a targeted observations mode, while the coherent aerosol system would provide continuous wind measurements from cloud layers and from within the boundary layer. Recent OSSE results indicate that a large portion of the DWL forecast impact can be obtained with only 10% - 15% of the data, using the targeted observations approach.

Table 3.1 Basic system parameters for a nominal hybrid DWL mission.

Table 3.1. Nominal parameters for two DWL technologies.

Parameter	Coherent	Direct
Wavelength (microns)	2.05	355
Energy/pulse (Joules)	0.250	0.2 @.355
PRF (design) (Hz)	10	100
Optical Efficiency (total)	0.35	0.3
Mixing Efficiency	0.42	N/A
Detector Efficiency	0.8	0.4
Collector Diameter (m)	0.5	0.75
Integration Time (sec)	15	15
Wallplug Efficiency	0.035	0.06 (@ 1.064)
Weight	TBD	TBD
Power w/o scanner (watts)	62 (peak & average)	850 Peak (225 average)

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 requirements of a space-borne 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 could comprise the hybrid DWL mission. Also, NASA is investigating innovative ways to improve scanning technology, as discussed in Section 5. The NPOESS Integrated Program Office has funded ground and airborne DWL demonstrations, proof of concept activities, OSSEs, and calibration/validation activities. In parallel with technology development and demonstration, OSSEs have been performed that show a lidar operating in a targeted observations mode should achieve a large portion of the benefits of a full 100% duty-cycle mission, but require substantially less power and volume.

Instrument power, mass, volume, and scanning requirements suggest a preference for a free flyer mission in the lowest practical orbit, on the order of 400 km. However, we are also investigating an NPOESS Pre-Planned Product Improvement (P^3I) mission to demonstrate a DWL and operationally useful data with constrained mass, power, and volume in an 827 km orbit. The P^3I program provides launch support and accommodation on the NPOESS spacecraft for instruments to demonstrate new or improved critical environmental data products. Operation from an 827 km NPOESS orbit requires more instrument capability to meet a given set of requirements as compared to operation from a 400 km orbit. Because of the recent NPOESS budget and schedule challenges, we are also investigating a possible DoD Space Test Program DWL demonstration mission.

4. What Type of Wind Information Will be Provided 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 line of sight (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 Fig. 4.1). The accuracy along the LOS would be ~1 ms^{-1} within the PBL and near cloud boundaries and ~2 to 3 ms^{-1} elsewhere. Depending on the lidar scanning pattern and sampling rate, the representativeness error 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.

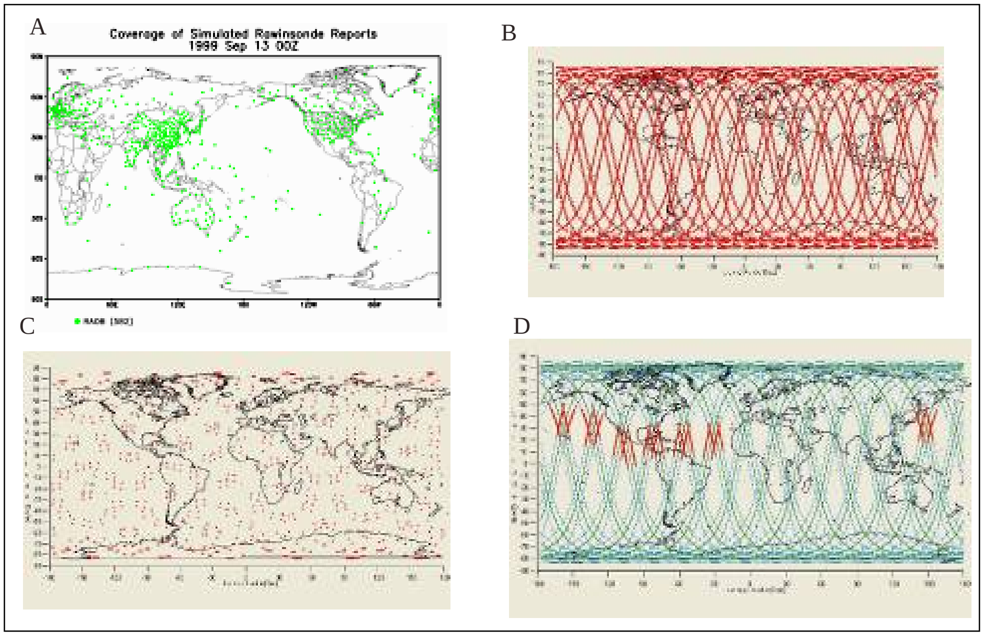
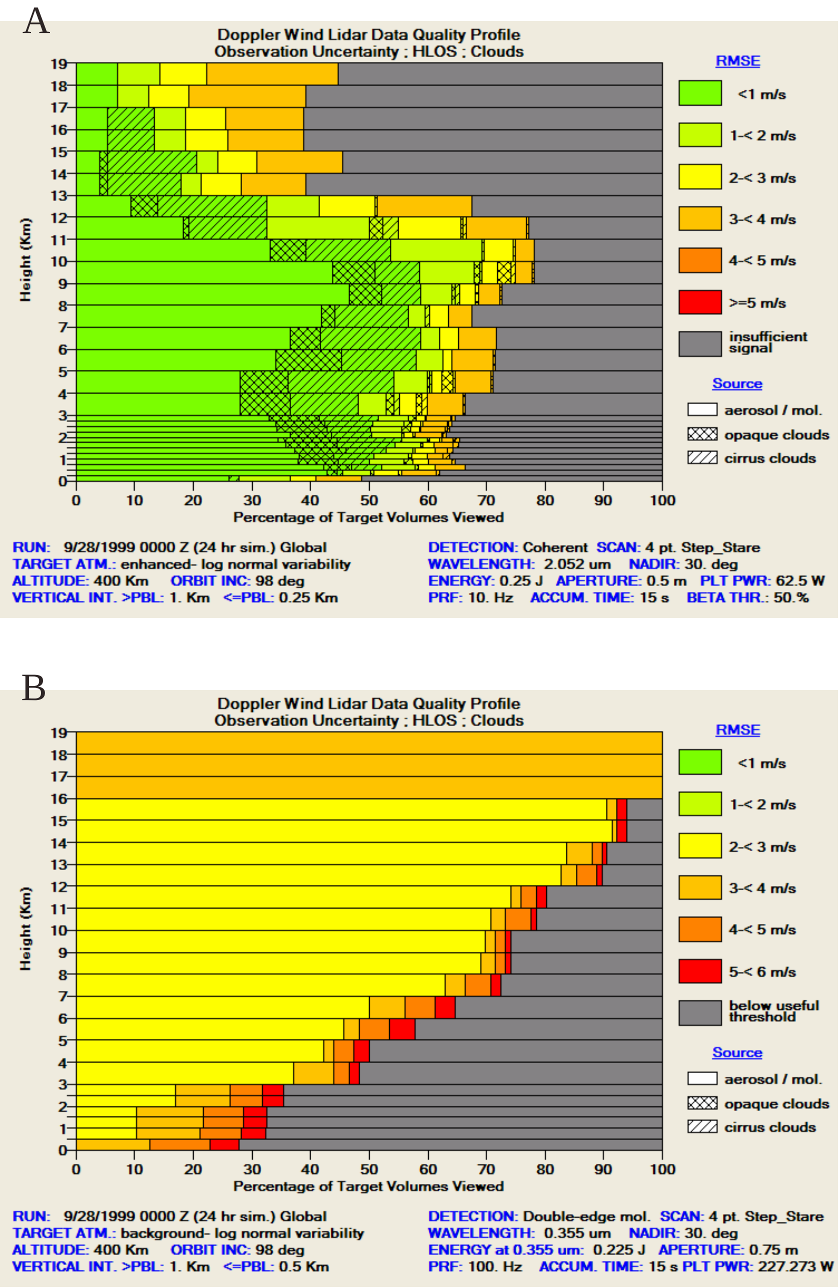


Fig. 4.1 Comparison of global rawinsonde coverage (A) with PBL wind profiles from coherent subsystem (B), direct detection subsystem with random global 10% duty cycle (C) and full tropospheric soundings using CONUS focused adaptive targeting (D)

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 Fig. 4.2. However, analyses of Lidar In-space Technology Experiment (LITE) data[8] and more recent data from the Geoscience Laser Altimeter System (GLAS) suggest nearly 60% “porosity“ for all clouds in the narrow lidar beam. Thus, while the global cloud cover is reported as being close to 80%, the lidar should penetrate to the ground ~ 70% of the time. Also, although clouds can attentuate or block lidar returns, the returns from clouds are very strong and can provide an independent wind observation and/or serve as a calibration point for cloud motion vector observations

An additional feature of the DWL wind product is the ability to assign a quality flag 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 measurement quality flag.



A

Doppler Wind Lidar Data Quality Profile
Observation Uncertainty ; HLOS ; Clouds

RUN: 9/28/1999 0000 Z (24 hr sim.) Global
TARGET ATM.: enhanced- log normal variability
ALTITUDE: 400 Km ORBIT INC: 98 deg
VERTICAL INT. >PBL: 1. Km <=PBL: 0.25 Km

DETECTION: Coherent SCAN: 4 pt. Step_Stare
WAVELENGTH: 2.052 um NADIR: 30. deg
ENERGY: 0.25 J APERTURE: 0.5 m PLT PWR: 62.5 W
PRF: 10. Hz ACCUM. TIME: 15 s BETA THR.: 50.%

B

Doppler Wind Lidar Data Quality Profile
Observation Uncertainty ; HLOS ; Clouds

RUN: 9/28/1999 0000 Z (24 hr sim.) Global
TARGET ATM.: background- log normal variability
ALTITUDE: 400 Km ORBIT INC: 98 deg
VERTICAL INT. >PBL: 1. Km <=PBL: 0.5 Km

DETECTION: Double-edge mol. SCAN: 4 pt. Step_Stare
WAVELENGTH: 0.355 um NADIR: 30. deg
ENERGY at 0.355 um: 0.225 J APERTURE: 0.75 m
PRF: 100. Hz ACCUM. TIME: 15 s PLT PWR: 227.273 W

Fig. 4.2 Summary diagrams of vertical coverage (accuracy and source) for two-DWL technologies (see Table 3.1) in areas where observations are attempted. Note that coherent detection (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).

5. How Ready are We for a Mission?

The key lidar technologies (including 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 space-based instruments with unique capabilities to observe surface and atmospheric properties in three dimensions. Today, NASA has four lidar systems in space: the Mars Orbiting Laser Altimeter (MOLA); the Geoscience Laser Altimeter System (GLAS); the Mercury Laser Altimeter (MLA); and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), launched in April 2006. Each successive lidar mission has demonstrated improved capabilities based on an expanded base of available technologies. GLAS and CALIPSO are making earth observations today.

Future global wind systems will build on this space heritage but require additional advances to meet the specific needs of the DWL measurement. For example, the precise nature of the Doppler frequency shift measurement requires high quality laser transmitter spectral properties (e.g., center wavelength, spectral line width). 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 stand-alone molecular direct detection DWL or a stand-alone coherent DWL inevitably leads to laser power and telescope/scanner aperture requirements well beyond current capabilities. On the other hand, recent studies indicate that a hybrid lidar combining a direct detection channel with a coherent detection channel will mitigate the large power and aperture requirements and reduce the complexity of scanning. 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 hybrid approach reduces spacecraft power and mass, making a mission 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 (including detectors, Holographic Optical Element (HOE) scanners, pump diode arrays, more efficient and higher power lasers, 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 Laser Risk Reduction Program (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 advance the Technology Readiness Levels (TRLs). The higher the TRL, the more mature the technology. A TRL of “8”, for example, would mean the technology has been demonstrated in space (see the Direct Detection seed laser, for example in Table 5.1). Assuming a successful ADM launch and operation, all of the major direct detection instrument components, except for the scanner, will have been demonstrated in space.

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 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.

5.1. Direct Detection Subsystem[12]

Table 5.1 shows TRLs of key components of the Direct Detection Subsystem of a hybrid DWL. Columns 3 and 4 show development activity and expected TRLs at the conclusion of the currently funded effort. 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 (Nd:YAG assumed) targets are 320 mJ at 50 Hz PRF, line width < 100 MHz, wall plug efficiency 2.5% or higher, 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 5.1 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 HOE attractive. Increasing laser power can reduce aperture size and scanner complexity. Recent government (NASA LRRP) and industry advances in laser power and efficiency promise a lighter and more robust instrument.

5.2. Coherent Detection Subsystem

Table 5.2 shows key component TRLs for the Coherent Subsystem of a hybrid DWL. This subsystem is based on a pulsed, solid state 2 micron laser. The 2 micron laser is being developed for space-based use at NASA Langley Research Center (LaRC) as part of the LRRP. The coherent lidar requires a frequency-agile 2 micron local oscillator laser. The coherent subsystem aperture is small enough to use a rotating optical wedge scanner rather than an HOE. The optical wedge scanner was developed and qualified for space as part of the Space Readiness Coherent Lidar Experiment (SPARCLE). Alternative designs using HOE or DOE technologies are at a lower TRL but could be used in a hybrid DWL. The 2 micron detector and integrated heterodyne receiver technologies are also being developed as part of the LRRP.

Table 5.2 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	4-5
Pre-Launch Lidar Photon Sensitivity Validation	3	From SPARCLE	3
Pointing, Nadir Compensation	7		7
Compensation Optics for Nadir Angle Tipping	2		2
Detector for Alignment Maintenance	2	U of CO	2
Space Environmentals	2	LRRP, IIP	3

Two micron system level demonstration is ongoing at LaRC in the ground-based Validar system. Airborne demonstrations are being conducted with systems such as Twin Otter DWL (TODWL), developed with Navy and IPO funding. Ground, airborne, and shipboard demonstrations are being conducted with systems developed at NOAA ESRL. The 2 micron lidar technology will be further advanced with currently funded IIP activities.

5.3. Scanning telescope for hybrid DWL

The scanning telescope is a critical space system element because of its mass, volume, and power requirements. GSFC Instrument Synthesis and Analysis Laboratory (ISAL) and Integrated Mission Design Center (IMDC) studies showed the feasibility of conventional optics for a coherent detection lidar. They recommended the HOE approach for a direct detection lidar to reduce mass and power for the rotated optical element. Advances since the ISAL (hybrid DWL, targeted observation strategies, more powerful and efficient lasers) promise to significantly reduce mass and power.

HOE. HOE scanners promise much lower mass, power, and momentum compensation requirements than conventional optics. NASA has been developing HOE scanning telescope technology for several years. Air and ground direct detection lidar demonstrations show reliable conical scanning with HOEs for 532 nm and 1064 nm wavelengths. 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 HOE optics up to 1-meter size and space-qualifying materials need to be addressed for a space-borne direct detection DWL. The 2001 ISAL study recommended an HOE for a free-flyer DWL over conventional optics. But the mass, power, and momentum compensation for an HOE were 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. NASA and industry projections for higher laser power and improved wall plug efficiency suggest that these problems can be alleviated by using much smaller apertures, which should be readily available at the time the hybrid instrument is designed (see Table 5.3).

ShADOE. The new Shared Aperture Diffractive Optical Element (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 1/3 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 5.1.

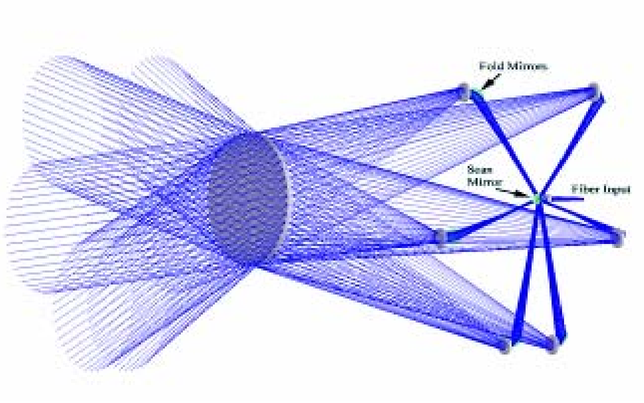


Fig. 5.1 Ray tracings for a ShADOE with six exposures, each oriented so the collimated portion is directed toward a central rotating scan mirror that sequentially addresses each FOV, directing the light to a single optical fiber.

Optics TRLs. Scanning telescope TRLs are shown in Table 5.3. 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. The estimated year to attain the new TRL is in parentheses in the last column.

Table 5.3 Scanning telescope TRLs.

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

For direct detection, ShADOE technology is at TRL 3. 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. 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 three years. Materials need to be space qualified early in the process since the technology is very material dependent.[17]

6. How Do We Proceed to Implement a DWL Mission?

Figure 6.1 illustrates the steps to achieve: (1) a space demonstration of a hybrid DWL and (2) the subsequent operational mission. A Multi-Agency DWL Working Group, composed of representatives from NOAA, NASA, and DoD, has been established to develop a joint DWL mission concept. Several options are being considered for demonstrating a hybrid DWL in space. NASA would be expected to take the lead in the development of the instrument. The DoD Space Test Program or the NPOESS Pre-Planned Product Improvement (P^3I) opportunity would provide the spacecraft, launch, and launch vehicle. The data processing, assimilation and forecast impact studies and instrument performance sensitivity studies would be supported by NOAA. NOAA, NASA, and DoD budget support is urgently needed, beginning in FY09, to begin to achieve the benefits of a space-based DWL in 2013. This is the earliest a space-based hybrid DWL demonstration can probably be launched in the U.S., *nearly five years after the first space-based DWL demonstration in Europe (via ADM).*

For the subsequent operational mission, NOAA would have the overall lead, but the NASA and DoD missions would also clearly benefit and be expected to contribute to the support of their respective users. An additional partner (working with NASA) for the instrument development would further strengthen the collaborative effort outlined above and is being pursued**.**

Figure 6.1 identifies activities leading to a DWL mission. The "Achieve Technology Readiness" activity will 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. The "Space Demonstration" will demonstrate technical capability and usefulness of winds data obtained with a hybrid DWL and targeted observations. The "Operational Mission" will involve acquiring, launching, and operating the instrument and spacecraft, communications, operations center, data production facility, and the production, distribution, and assimilation of the data products.

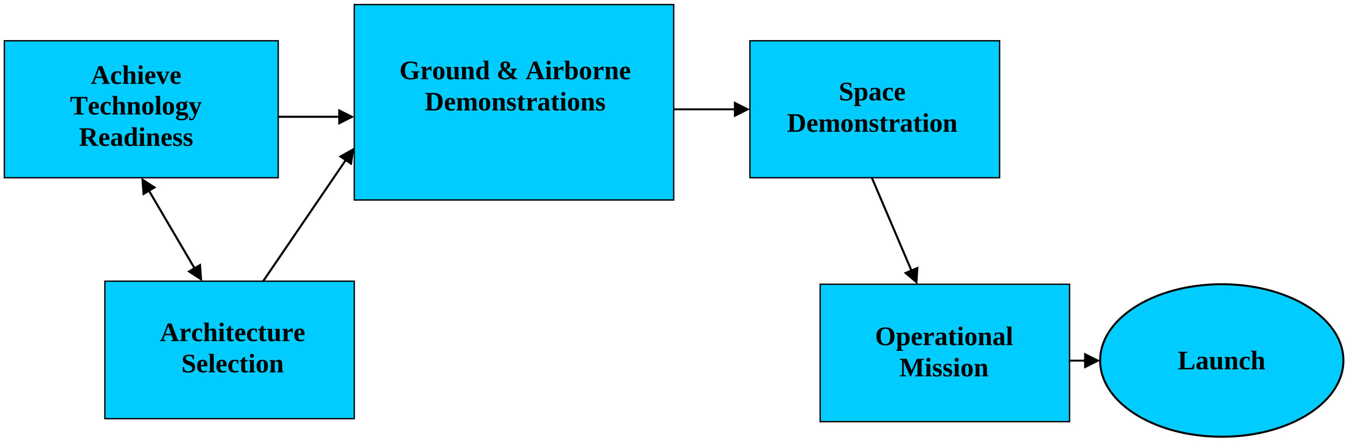


Fig. 6.1 Activities leading to a DWL Mission.

7. DWL Mission Elements and Costs[1]

Major elements for a hybrid DWL demonstration mission include instrument development, spacecraft integration, launch, and operations. These elements were analyzed by GSFC design teams[2] in 2001 - 2002. Since that time, the mission concept has advanced to flying a hybrid DWL on a free flyer platform, ideally in a 400 km polar orbit because of the signal-to-noise advantage compared to higher orbits. The hybrid DWL is expected to reduce overall costs and shorten the instrument development timeline. A candidate launch opportunity via the DoD Space Test Program is being investigated. Another candidate is an NPOESS P^3I mission.

Instrument: The major concerns identified by the GSFC design effort in 2001 – 2002 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, the hybrid instrument point design[3] and studies using targeted observations[6] have significantly reduced all of these concerns. Subsequent technology development[3,4,5] has significantly advanced component technologies. The remaining required instrument activities include:

- Laser, detector, telescope, scanning, and pointing component development to attain performance, technology readiness, and 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. The ISAL studies in 2001 proposed design approaches for momentum compensation and pointing and concluded that the requirements can be met in a free-flying spacecraft. The momentum compensation challenge has been reduced since 2001 by the hybrid DWL architecture and more powerful lasers becoming available. Increased laser power allows the use of smaller apertures. HOE scanners use a flat rotating disc and can be both lighter and better balanced than conventional optics. Pointing system designs were proposed by the ISAL/IMDC studies.[2] A system was recently presented[16] to meet pointing requirements for a coherent lidar space mission using techniques similar to those used for the GLAS/ICESat mission.

Launch: Studies at the GSFC 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 the use of a smaller launch vehicle.

Operations: The first U. S. DWL space mission will provide operationally useful data as well as a technology demonstration. Communications requirements can be met with available capabilities.

Cost: The estimated cost of a hybrid DWL space demonstration is \$300 M to \$350 M to complete component development, conduct ground-based and airborne tests of the hybrid DWL, integrate the spacecraft, launch, conduct mission operations, assimilate data, perform forecast impact studies, and conduct instrument performance studies. The cost of the subsequent operational mission is estimated to be \$250 M to \$300 M, with the somewhat lower cost reflecting the benefits of the space heritage of the technology flown on the demonstration mission.

8. Summary

Global winds observations are a vital national need with a broad range of societal benefits, and “wind profiles at all levels” is listed as the number one priority of the USIEOS Strategic Plan. The European Space Agency is planning to launch the first DWL into space in late 2008, *with technology pioneered in the United States*. With a budget initiative beginning in FY09, the earliest a DWL can be demonstrated in the United States is probably 2013.

The hybrid DWL is a promising instrument approach. The enabling technologies are rapidly maturing, and budget support is needed to conduct ground, air, and space demonstrations, in order to provide the missing link in the global observing system.

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