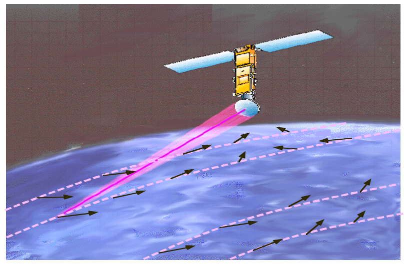
Space-based Doppler Winds LIDAR: A Vital National Need



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May 2005

In response to National Research Council (NRC) Decadal Study
Request For Information (RFI)

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2 Executive Summary

In response to the National Research Council (NRC) Decadal Study Request for Information (RFI), we would like to propose a space-based Doppler winds *LIght Detection And Ranging* (LIDAR) demonstration mission with a targeted launch date of 2011-2012. The mission will address our vital national needs for high-resolution global tropospheric wind observation, which will lead to improved long-range weather forecasting, more accurate hurricane landfall prediction, improved climate models, better battlefield environmental predictions for military operations, more accurate upper-tropospheric/lower-stratospheric winds for Air Force operations, and potential chemical-biological release trajectory prediction for homeland security operations. The launch of a space-based winds LIDAR demonstration mission in the 2011-2012 time frame is critical to enable operational winds LIDAR on the National Polar Orbiting Environmental Satellite Systems (NPOESS) in the 2015-2016 time frame. Global tropospheric wind profiles are the #1 unmet Environmental Data Record (EDR) of NPOESS. This is especially urgent since the US, as a world leader in space technology and Earth observation, is falling behind Europe and Japan in space-based winds LIDAR development and deployment. As a result of strong government and private industry investment in the last 5-10 years, all key technologies for space-based direct-detection Doppler winds LIDAR have reached Technology Readiness Levels (TRL) of 5-7. The cost of such a mission, estimated at about $200M, is clearly well justified based on its very strong national needs and significant societal benefits. There is a strong consensus in the operational agencies and user communities that space-based winds LIDAR mission should be considered as a top priority for future space missions. Mission planning and phase A/B study must commence immediately to enable a launch in 2011-2012.

3 Applications & Need for Global Winds

Throughout history, various wind measurement techniques have been employed, ranging from human observation to sophisticated wind LIDARs. Wind vanes were used by the ancient Egyptians and Chinese to measure the direction of air flow. The Greeks measured winds by observing the directions and deformation of trees and grass fields. Aristotle wrote about relationships between cloud formation and winds. Despite this long history of interest, there is still no direct measurement of global wind profiles throughout the troposphere and lower stratosphere (approximately 0 to 30 km). Today such measurements are critical for improving long-range weather forecasting, hurricane tracking, troposphere-stratosphere exchange studies, global pollution tracing, and climate studies. The World Meteorological Organization (WMO) has consistently ranked direct observation of global winds profiles from satellites as one of the most challenging and important observations.

The current knowledge of atmospheric dynamics and processes can be gauged by the effectiveness of modern Numerical Weather Prediction (NWP). NWP relies on input data to characterize the initial state of the atmosphere, and computational models to predict its spatiotemporal evolution. Advancements in atmospheric models and computing power over the years have far out-gained the improvement in atmospheric observations. Thus, the most productive step toward an improved understanding of atmospheric processes, weather, and climate change involves new atmospheric measurements that can fill the gaps of our data. Accurate modeling of atmospheric dynamics requires 4-dimensional input data (volumetric data over time) for the balancing of energy, mass, and momentum. These measurements include temperature, radiance, albedo, composition, humidity, pressure, and wind velocity, all of which are measured from ground, ocean, balloon, and satellite platforms. Modern wind measurements are limited and do not provide the volumetric density nor the sampling to reach the full potential of NWP. The National Oceanic and Atmospheric Administration (NOAA) and WMO recognizes that global tropospheric wind data are the single most important input measurement required to improve NWP.

The current wind measurements include ground stations, buoys, ships, radiosondes, aircraft, ground-based wind profilers, and radiometer, scatterometer, and cloud tracking satellites. Table 1 summarizes these measurements. The ground stations (ASOS, Weather Bug), buoys networks (MON, TAO), ships (VOS), and scatterometers (NSCAT, SeaWinds) provide good coverage; however offer little atmospheric profile information. Ground-based wind profilers (NEXRAD) offer superior wind measurements when aerosols or clouds are present. Cloud tracking satellites (Meteosat) provide wind measurements at locations and altitudes where clouds or aerosols exist but with poor altitude resolution. Water vapor channels on space-based radiometers (SMMR, TOV) provide wind velocity as a secondary data product, but again with poor accuracy and resolution. Radiosondes (RaObs) and aircraft (ACARS) measurements provide good wind profiles, but are primarily performed over well-populated regions in the northern hemisphere. Few wind measurements are performed in the clear-air over the oceans and southern hemisphere. Figure 1 illustrates the sparseness of these measurements, and the capability of a global tropospheric wind LIDAR to fill the measurement voids. The high value of tropospheric wind for improved weather prediction and climate studies is highlighted by the fact that it is ranked as the highest priority unmet measurement by NPOESS/IPO, a joint office representing DOD, NOAA, and NASA.

Table 1. Summary of wind measurements currently used for NWP.

Instrument Type	Altitude	Wind Accuracy	Coverage	Conditions
Ground stations	Ground-level	<1 m/s	Land	All
Buoys	Sea-level	1 m/s	Ocean	All
Ships	Sea-level	1 m/s	Ocean	All
Radiosondes	0:30 km	>1 m/s	Mostly NH Land	All
Aircraft	0-20 km	2-5 m/s	Mostly NH Land	All
Wind Profilers	Aerosol level	1 m/s	Land	Aerosols/clouds
Radiometer satellites	0-30 km	>2 m/s	Land & Ocean	Humidity/clouds Not independent
Scatterometers	Sea-level	2 m/s	Ocean	Clear skies
Cloud tracking satellites	Cloud-top level	>3 m/s	Land & Ocean	Cloudy skies

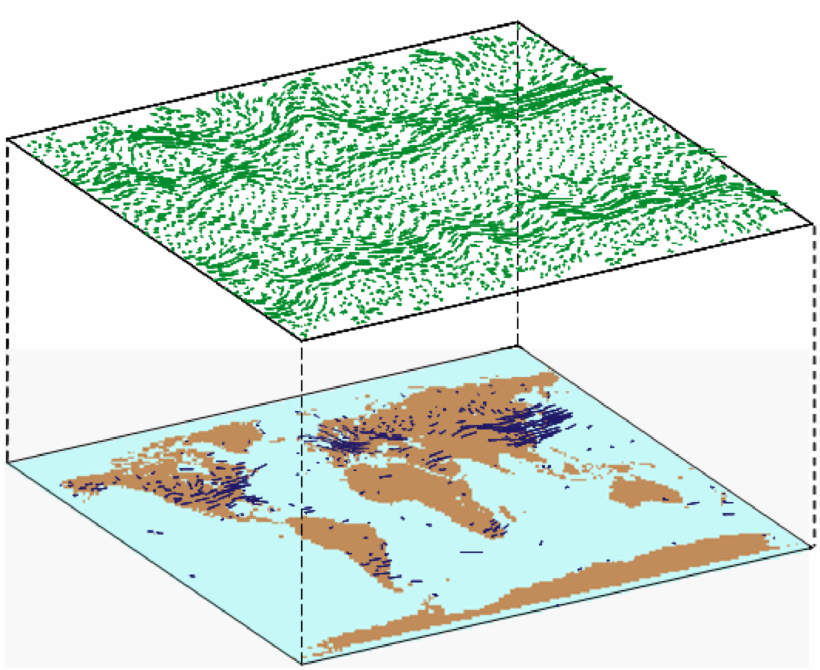

Figure 1: Points in blue are the existing locations of Radiosonde stations. The green points represent the global sampling that can be achieved with a space borne Doppler wind LIDAR.

Doppler Wind LIDAR (DWL) is a general term for an active remote sensing instrument that uses aerosol and/or molecular backscatter to measure wind. Specifically, the atmospheric backscatter from a laser pulse is collected by a telescope, range-gated, and spectrally analyzed to determine the Doppler shift. The range gates, Doppler shift, telescope look-angle and satellite orbit can be used to calculate the wind velocity in the ground frame as a function of altitude. Global tropospheric winds can be measured from a satellite using this method. DWL instrument concepts can be divided into two main categories: Direct detection and coherent detection. These techniques are viable only if they are able to collect sufficient backscatter from regions with low aerosol content and produce a useful velocity measurement that helps fill the data void over the oceans and southern hemisphere.

A space-borne DWL instrument is seen as an enabling technology that would provide global tropospheric wind measurements, improved NWP, and subsequent socio-economic benefits. Numeric simulations have been performed to determine the impact of different DWL performance specifications on NWP. One such simulation technique used by NOAA and NASA scientists is called the Observing System Simulation Experiments (OSSEs). OSSEs have repeatedly shown that the greatest impact to weather forecasting will come from full-tropospheric soundings, clouds permitting, with a scanning telescope. Simulations performed by the European Center for Medium range Weather Forecasting (ECMWF) use a different simulation technique, yet produce similar findings.

The Global Tropospheric Wind Sounder (GTWS) Science Definition Team (SDT) is a joint NASA-NOAA effort formed to generate a set of data requirements for space-borne DWL instruments. The data requirements are intended to guide the design of future instruments in order to ensure a positive impact on science and operational weather forecasting. These requirements are based on the abilities of current wind profilers and the results of OSSEs. Table 2 shows the threshold and objective requirements for a space-borne Doppler wind LIDAR instrument defined by the GTWS SDT. The threshold requirements represent the minimum data requirements, whereas the objective requirements define the desired data product for the greatest impact. The requirements in Table 2 were formulated with consideration of the technological issues associated with the state-of-the-art of LIDAR technologies and the logistical issues with twice-a-day global coverage performed by a single space-borne instrument. Table 2 shows the corresponding set of specifications devised by ECMWF to be nearly identical.

Table 2. GTWS and ECMWF data product requirements for a space-borne Doppler Wind LIDAR. TSV is an acronym for Target Sample Volume.

	GTWS Threshold	GTWS Objective	ECMWF Objective
Depth of Regard (DOR)[km]	0-20	0-30	0-20
Vertical TSV resolution [km] DOR top to tropopause Tropopause to boundary layer top Boundary layer top to ground-level	 Not required 1.0 0.5	 2.0 0.5 0.25	 2.0 1.0 0.5
Horizontal TSV dimension [km] (maximum averaging)	100	25	50
Horizontal location accuracy [km]	0.5	0.5	N/A
Horizontal resolution [km] (distance between TSVs)	350	100	200
Number of LOS perspectives in TSV	2	2	1
Accuracy (1-σ) of LOSH [m/s] Above boundary layer Within boundary layer (# in () is σ_s within TSV)	 3.0 (1.2) 3.0 (1.2)	 2.0 (1.4) 1.0 (1.0)	 3 2
Horizontal component bias [m/s]	0.1	0.05	N/A
Maximum horizontal speed [m/s] Above boundary layer Within boundary layer	 75 50	 100 50	 N/A N/A
Temporal resolution [hours] (revisit period)	12	6	12
Data product latency [hours]	2.75	2.75	3

The societal, economic and scientific impact of a space-borne DWL that meets the GTWS SDT data specifications is wide-spread [1,2,3]. Vastly improved weather forecasts will be the primary societal impact, including the improvement of regional meteorological forecasts (temperature, visibility, sky conditions, pressure, humidity, and wind), air quality forecasts, and severe weather forecasts. The improved weather and air quality forecast will improve decisions in commerce, health, and other weather-dependent fields. More accurate forecasting of severe weathers, such as improved hurricane tracking, will save lives and properties through more

[1] M. Masutani, J.C. Woollen, S.L. Lord, J.C. Derber, G.D. Emmitt, S.A. Wood, S. Greco, J. Terry, R. Atlas, and T.J. Kleespies, "*Impact Assessment of a Doppler Wind Lidar for NPOESS/OSSE*", AMS Sixth Symposium on Integrated Observing Systems, Orlando, Florida, January 2002.

[2] W.E. Baker, G.D. Emmitt, F. Robertson, R.M. Atlas, J.E. Molinari, D.A. Bowdle, J. Paegle, R.M. Hardesty, R.T. Menzies, T.N. Krishnamurti, R.A. Brown, M.J. Post, J.R. Anderson, A.C. Lorenc and J. McElroy, "*Lidar-measured winds from space: A key component for weather and climate prediction*", Bull. Amer. Meteor. Soc., 76, 869-888, 1995.

[3] J. J. Cordes, "Economic Benefits and Costs of Developing and Deploying a Space-Based Wind LIDAR", Final Report for NWS, NOAA, and US DoC, March 1995.

efficient evacuations. The American public is increasingly demanding this capability as demonstrated in the 2004 hurricane Charley. For example, several articles have been published in USA Today on the inaccuracy of hurricane Charley's landfall and track prediction that led to loss of lives and properties in areas that were not forecasted to be in hurricane Charley's track, and therefore, were not properly evacuated

The economic benefits provided by a space-borne DWL include more intelligent and efficient environmental policies, reduced over-warning of severe weather events, and reduced airline fuel consumption from improved forecasts and planning. Such benefits are estimated to save about $200M per year in 1994 U.S. dollars[3]. The required accuracy, resolution, and coverage required to realize these benefits are not possible with the current passive remote sensing technology, nor feasible with the current profiler and sounding systems. The economic impact of global tropospheric winds on the U.S. will pay for the space-borne DWL mission in the first year.

The scientific impact is the advanced understanding of the Earth's atmosphere from the unprecedented measurement. Consistent and long-term observations of global tropospheric winds profiles can be used to monitor seasonal variations and eventually climate variability and changes. Of particular interest are the bulk kinetic energy in the atmosphere and its correlation with thermal energy (global warming) trends and changes in circulation patterns caused by global warming-induced melting of the polar ice caps and ice sheets. The continual monitoring and measurement of the Earth's velocity field will be a key component to future long-term monitoring and climate prediction models. The secondary data products that result from some DWL techniques, although less accurate than other measurement methods, may be found useful. These products include aerosol backscattering coefficient profiles, extinction profiles, and temperature, all of which are important to climate forcing and global warming studies.

4 Technology Overview and Readiness Assessment

4.1 Overview of Doppler Wind Lidar Technology

LIDAR systems generally consist of three major optical subsystems, which are the laser transmitter subsystem, the telescope subsystem, and a detection/receiver subsystem. The laser transmitter subsystem has been the technology "tall pole" that has prevented broader deployment and utilization of space-borne LIDARs for both civilian and military applications despite the high scientific potential and strong need However, the significant technology advancements made possible by substantial government and industry investments, which are discussed below, are rapidly changing this assessment and are making operational space-borne LIDAR systems more feasible. A scanning telescope is necessary to measure line-of-sight wind speed from multiple look angles to determine the wind speed and direction in a target volume. Requirements analysis and performance trade studies conducted over the past decade have indicated that these "looks" need to be from a step-and-stare configuration as opposed to a continuous scanning configuration. The implication of this requirement is that a telescope must be accelerated and decelerated at a relatively rapid rate to point to the same target volume from a forward and aft direction, which poses a challenge for platform stabilization. The detection/ receiver subsystem is considered to be the most technologically advanced subsystem of the wind LIDAR instrument. There are a variety of proven techniques with different capabilities, which are discribed below.

In this section, we will first discuss the basic concept of Doppler winds LIDAR. Then we will present a detailed assessment of the technology readiness level (TRL) of the three key subsystems of the proposed direct-detection Doppler winds LIDAR, namely the laser transmitter subsystem, the scanning telescope subsystem, and the receiver subsystem. Our assessment indicate that all key subsystems are at TRL 5-6 or higher and should allow the beginning of space-borne Doppler winds Phase A/B program with acceptable technical, schedule and cost risks that are comparable to many previous and current passive and active space sensors.

4.1.1 Coherent & Direct-detection Doppler Wind Lidar

Two different methods for measuring the Doppler shift of backscattered laser light have emerged as potential methods for making global wind observations from space. The direct-detection method, which uses high-resolution optical devices such as a Fabry-Perot etalons, detects the Doppler shift directly from spectrum of light backscattered from atmospheric air molecules and aerosols. The other approach is optical heterodyning, or coherent detection, which measures Doppler shifts by beating the backscattered laser light with a laser source from a stable local oscillator. Coherent techniques use the same basic principles as Doppler radar, and rely on backscattering from atmospheric aerosols. Using coherent detection can provide very accurate winds measurements in atmospheric regions with adequate amount of aerosol particles such as the boundary layer. This is in contrast to direct detection, which is able to measure winds from molecular backscatter independent of the aerosol field. The ability of direct detection to measure winds in clean air makes it an attractive operational space-borne Doppler winds LIDAR technique to cover the whole troposphere and lower stratosphere (0 – 20 to 30 km), which is required by the data user communities. Both direct detection and coherent detection have their advantages and disadvantages depending on the types of applications and measurement requirements. They can complement each other in that the coherent detection can target the boundary layer (i.e. 0 – 3 km) and direct-detection targets the middle and upper troposphere (3 – 20 to 30 km). This hybrid approach to space-borne wind LIDAR has been suggested by Emmitt[4]. However, the focus of this white paper is to detail the direct-detection Doppler wind LIDAR technology and readiness assessment. The discussion is relevant for the direct-detection system to be implemented as a stand-alone instrument or part of a hybrid system.

The complementarily that exists between coherent and direct-detection techniques has precipitated hybrid concepts to be formed to meld the different sensing technologies for a satellite observing system. This "best of both worlds" approach, it is believed, has advantages in that the size, weight, power requirements of an individual system exceed that of the combined system to meet the same performance over all measurable and desired conditions. However, to date, a hybrid instrument has never been demonstrated even though several instruments of each type have been demonstrated individually. The heritage of coherent wind LIDARs extend back to the 1960s and have included ground based and aircraft systems. NASA and NOAA, and several industry technology leaders, develop and utilize coherent wind LIDAR for scientific and technology field studies. Examples of modern direct-detection systems include the NASA Goddard GLOW instrument and the instruments developed through the NOAA GroundWinds program. Another important direct-detection wind LIDAR instrument is the Atmospheric Laser Doppler Instrument *(ALADIN*) developed by the European Space Agency (ESA), which will be launched on the ADM-Aeolus satellite in October 2007.

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[4] Emmitt, G.D: Hybrid technology Doppler wind LIDAR: assessment of simulated data products for a space-based system concept., SPIE Lidar Remote Sensing for Industry and Environment Monitoring, Sendai, Japan. October 2000.

4.1.2 Direct-Detection Doppler Wind Lidar

The two most common direct-detection techniques for measuring the Doppler shift from atmospheric backscatter are the double-edge[5] and the fringe-imaging[6] method. Several double-edge and fringe-imaging systems have demonstrated the efficiency of each technique in measuring the Doppler shift from atmospheric molecular and aerosol backscatter. The most notable systems are the double-edge GLOW instrument developed by NASA Goddard[7], and the GroundWinds [8] multi-order, photon-recycled fringe imaging systems in New Hampshire (GWNH), Hawaii (GWHI)[9] and the BalloonWinds instrument, which are funded by NOAA and are being developed by the University of New Hampshire (UNH), Michigan Aerospace Corporation (MAC), Raytheon, and Fibertek. Common to most direct-detection instruments that have been proposed and developed for global wind sounding is the use of tunable Fabry-Perot etalons to resolve the wavelength of the backscatter. Many system implementations, including GLOW and GroundWinds, often employ two Fabry-Perot interferometer channels combined into a single receiver that are independently optimized to sense the Doppler shift from aerosols and molecules. A notable exception is the aerosol channel of the ADM-Aeolus Atmospheric Laser Doppler Instrument *(ALADIN*), which uses a Fizeau interferometer but employs a Fabry-Perot for the molecular channel. While the molecular channel of these instruments retain sensitivity to aerosols, the aerosol channel provides superior accuracies when aerosols are present. The dual channel configuration would be advantageous for a satellite wind system if a direct-detection system were the only instrument. An aerosol channel would provide more detail on scattering from clouds as well as provide an accurate ground echo, which is useful for calibration since the ground provides a true Doppler zero reference. In a hybrid (coherent & direct) system, the use of the aerosol channel would not be necessary because the coherent wind sensor would provide the needed measurements from aerosols.

The laser wavelength that would be employed for a space-borne wind LIDAR is 355 nm, or the 3rd harmonic of Nd:YAG lasers. This offers the optimal signal return for sensing the wind field from clear air because the molecular backscatter is proportional to $1/\lambda^4$ but shorter wavelengths (such as 266 nm) suffer to much attenuation by the atmosphere. The molecular channel of the GLOW system, and the molecular and aerosol channel of the GWHI system operate at 355 nm. An important advantage of using 355 nm for direct detection is that the Nd:YAG laser technology for generating this wavelength is currently the most mature laser transmitter technology for space applications.

While the aforementioned direct-detection systems employ Fabry-Perot etalons as the wavelength resolving element, they can be used in a variety of implementations. Described in Figure 2 are the main differences between the double-edge method and the fringe imaging method. The double-edge method measures the Doppler shift from the relative intensities in two spectral edge filters positioned symmetrically about the central laser frequency (or *Zero Wind*), Figure 2. The signals collected from the spectral edges are captured by single element detectors such as Photo-Multiplier Tubes (PMTs) or Avalanche Photo-Diodes (APDs). Range gating the

[5] C.L. Korb, B. M. Gentry, and C. Y. Weng, "Edge technique, theory and application to the LIDAR measurement of atmospheric wind," Appl. Opt., **31**, 4202-4213 (1992).
[6] J.A. McKay, "Modeling of direct detection Doppler wind LIDAR: II. The fringe imaging technique," App. Optics, 37, 6487-6493, 1999
[7] B.M Gentry, H. Chen, and S. Li. "Wind Measurements with a Molecular Doppler Lidar". Optics Letters, 25, 1231-1233. 2000
[8] P. B. Hays and C. A. Nardell. "GroundWinds: A Direct Detection Doppler LIDAR Technology Demonstration", Invited Paper, , SPIE 2nd Asia-Pacific Remote Sensing Conference, Sendai, Japan, October 2000
[9] "Performance and comparison of 532nm and 355nm groundwinds LIDARs", M. T. Dehring, C. A. Nardell, J. C. Pavlich, P. B. Hays, I. G. Dors. SPIE Remote Sensing conference, Hangzhou, China, October 2002

backscattered signal collected with these devices from a satellite could be accomplished with photon counters. Due to the low spectral sampling inherent to double-edge systems wind speed has to be determined by applying line-shape models that can accurately represent the temperature and Doppler response, which requires that the atmospheric temperature and aerosol contribution to the signal be explicitly known prior to analysis. Despite the low spectral sampling of the double-edge technique, the use of single element detectors confers simplicity and low cost.

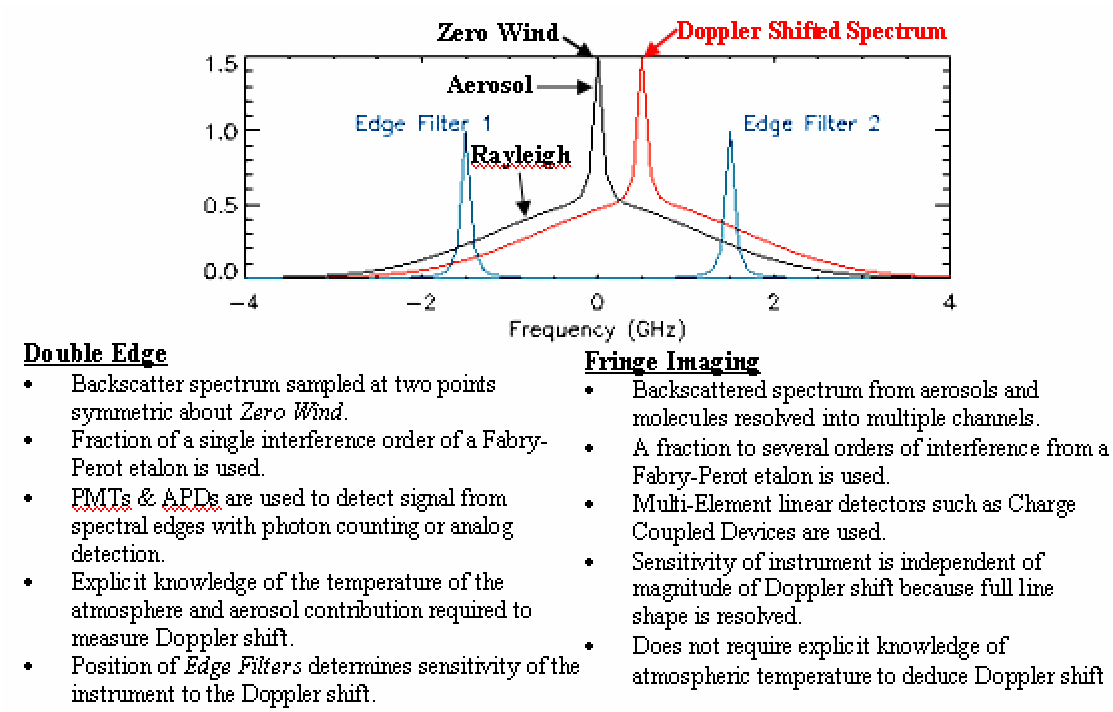


Figure 2: The plot above depicts the representative composite Doppler-shifted and unshifted lineshape spectrum from aerosols and molecules (Rayleigh). Also, depicted in the figure are edge filters to indicate the way a double-edge instrument samples the spectrum; fringe imaging instruments resolve the full spectrum in to many channels, number of channels ranges from 10 to over 100.

Fringe imaging instruments[10], such as GroundWinds[11], resolve the backscattered spectrum from aerosols and molecules into multiple spectral channels and can thus use multiple orders of interference from the Fabry-Perot etalons (see Figure 3). The enabling technologies central to the GroundWinds fringe imaging direct-detection Doppler wind LIDARs are photon recycling (U.S. patent #6,163,380), the Circle to LIne Optic (CLIO- U.S. Patent #4,893,003) and use of highly efficient Charge Coupled Devices (CCDs). Photon recycling is a technology that enhances the overall throughput and net efficiency of a Fabry-Perot Etalon (FPE) by up to a factor of 5. In Figure 3 the right most 4 orders of interference are contributed by photon-recycling. The gain in signal by implementing photon recycling has a high potential for lowering the requirements on laser power and telescope aperture size for a satellite observing system. The enhanced spectral resolution of the fringe imaging technique enables the measurement of wind speed as well as other optical properties such as aerosol contribution to the total collected backscatter and temperature. The random thermal motion of molecules, which is proportional to temperature, determines the width of the backscattered spectrum and can be directly measured

[10] M.J. McGill and J.D. Sphinhirne, “A Comparison of two direct-detection Doppler LIDAR techniques”, Opt. Eng 37, 2675-2687, 1998

[11] J. Wang, M. Dehring, C. A. Nardell, P. B. Hays, D. Dykeman,, & B. Moore III. “Direct Detection Doppler Winds Lidar: Ground-based Operation to Space”, SPIE Optical Science and Technology. San Diego, CA August 2003.

with a fringe imaging system. Multi-order fringe imaging LIDARs, such as GroundWinds, achieve much higher spectral resolution than the double-edge based techniques however they require more complicated detectors (such as CCDs). As will be demonstrated in the BalloonWinds[12] instrument, a single CCD can be used for both of its optimized channels, which has several system benefits such as a reduction is size, weight, power, and data bandwidth than implementing separate detectors for each channel.

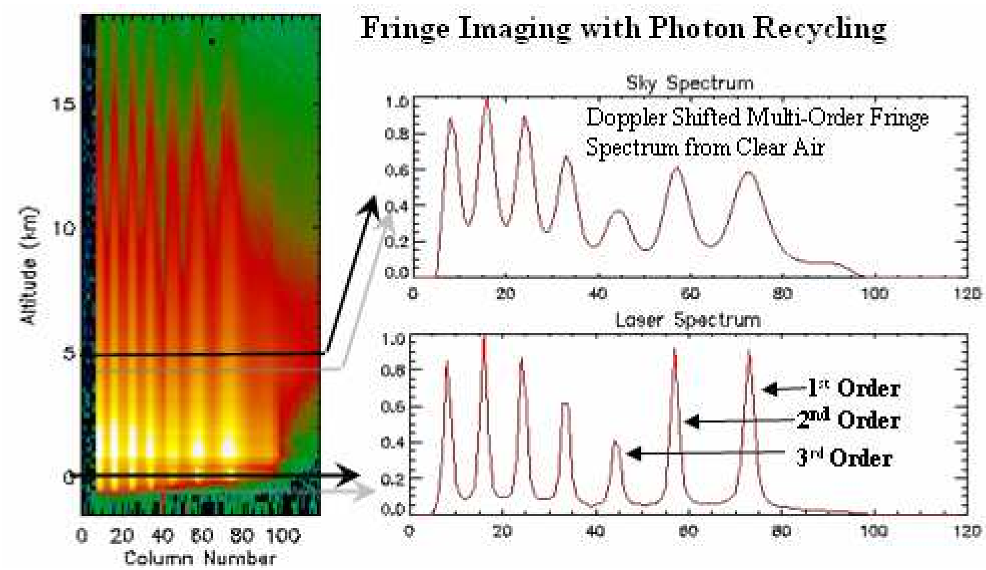


Figure 3: Plot on the left is a fringe image taken with the molecular channel of the GroundWinds HI interferometer. The two plots on the right are the spectrum from the laser, bottom right, and backscattered spectrum from an altitude of 5 km, top right. The lines draw over the fringe image depict where the spectra are located in the image. Note that there are 7 interference orders imaged onto the CCD, the right most 4 interference orders are contributed from photon recycling.

Both the fringe imaging and double-edge technologies are well suited for satellite implementation. The ESA ALADIN uses both fringe imaging and double edge in its receiver subsystem. ***Through creative implementations of photon-recycling and novel receiver design it may be that a combined approach, which melds the best aspects of fringe imaging and double-edge techniques, will provide the most valuable solution for future satellite-based direct-detection Doppler wind LIDAR.***

4.2 Laser Transmitter Technology and Readiness

<u>TRL Summary</u>: Direct-detection Doppler wind LIDAR Nd:YAG laser transmitter is determined to be at TRL of 5-6. This assessment is based on: (1) Nd:YAG is the most mature solid-state laser technology with a long history of industrial and space applications; (2) the recent Nd:YAG laser transmitter (250 mJ/pulse at 1064 nm, 20 Hz) development for the NASA ESSP CALIPSO instrument; (3) Nd:YAG laser transmitter (400 mJ/pulse at 1064 nm, 100 Hz) for the European Space Agency (ESA) ADM-Aeolus ALADIN Doppler winds LIDAR; (4) the development of a risk reduction laser transmitter prototype by Raytheon and Fibertek (1J/pulse at 1064 nm, 50 Hz) for the proposed Doppler winds LIDAR demonstration mission.

[12] M. T. Dehring, J. M. Ryan, P. B. Hays, B Moore III, J. Wang. "GroundWinds Balloon Fringe Imaging Doppler LIDAR Mission Concept and Instrument Performance" SPIE Remote Sensing of the Atmosphere, Environment, and Space, Honolulu, Hawaii, November 2004

One of the critical subsystems for any space LIDAR mission is the laser transmitter. Of all the laser transmitter types proposed for space applications, diode-pumped Nd:YAG solid-state lasers are the most mature and have the greatest space heritage. Nd:YAG laser technology is one of the most widely used in a variety of commercial and space applications. Considerable investment has been made by government and private industries to advance Nd:YAG laser. Many past and current space-borne LIDAR missions have used Nd:YAG lasers. These include *Mars Orbiter Laser Altimeter (MOLA)*, *Near Earth Asteroid Rendezvous (NEAR)*, *Mercury Laser Altimeter (MLA)*, *Geoscience Laser Altimeter System (GLAS)* on *ICESAT* launched in January 2003, *Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)* scheduled for launched in 2005, ESA *ADM-Aeolus ALADIN*, a direct-detection Doppler Wind Lidar, to be launched in late 2007.

The GLAS laser transmitter is a diode-pumped Q-switched Nd:YAG laser with 75 mJ/pulse at 1064 nm, 35 mJ/pulse at 532 nm, and a pulse repetition rate of 40 Hz. Despite problems with the pumping diode arrays, GLAS has provided unprecedented data on ice sheet height and atmospheric clouds and aerosol, thus validating the tremendous value of space-borne LIDAR remote sensing. The problem with the pumping diode arrays was due to the process and workmanship associated with diode arrays in the early 1990s. The CALIPSO instrument is an aerosol and cloud LIDAR developed under the NASA ESSP program. Its laser transmitter consists of two redundant diode-pumped and Q-switched Nd:YAG lasers, each of which generates 250 mJ/pulse at 1064 nm with a pulse repetition rate of 20 Hz. The laser was successfully developed and space-qualified by Fibertek, Inc. CALIPSO was successfully integrated into the spacecraft and is ready for launch. ADM-Aeolus is the 2nd core mission of the European “Living Planet” program. The payload is a direct-detection Doppler LIDAR called Atmospheric Laser Doppler Instrument (ALADIN). It is designed to provide tropospheric and lower stratospheric winds profile data and to demonstrate its applications in improving numerical weather forecasting and climate studies. It uses a diode-pumped Q-switched Nd:YAG laser transmitter with about 400 mJ/pulse at 1064 nm, which is converted to more than 150 mJ/pulse 355 nm output through 2nd and 3rd harmonic generation. It is operated at a pulse repetition rate of 100 Hz.

The development, space qualification, and operation of high energy diode-pumped solid-state Nd:YAG laser transmitters for the IceSat GLAS, CALIPSO, and ADM-Aeolus ALADIN have significantly advanced the technology readiness level (TRL) of Nd:YAG laser transmitter for space applications for direct-detection systems. NASA has also initiated and funded the Laser Risk Reduction Program (LRRP) since 2000 to improve the overall space-borne laser technology readiness level. The LRRP is being lead by Dr. Upendra Singh from NASA Langley Research Center (LaRC) and Dr. William Heap from NASA Goddard Space Flight Center (GSFC). NASA LaRC has been focusing on the advancement of 2-μm solid-state laser technology for space-borne coherent wind LIDAR and CO2 profiling LIDAR. NASA GSFC has been focusing their efforts on diode-pumped 1-μm Nd:YAG laser technology. Significant progress has been made in understanding the failure mechanisms of pumping diode arrays, improving laser wall-plug efficiencies, and developing contamination control procedures and thermal management approaches. In parallel to the NASA funded LRRP, Raytheon initiated an Internal Research and Development (IRAD) program in 2002 and partnered with Fibertek to develop a space-qualifiable 1-J/pulse, 1064-nm, 50-100 Hz, compact, and rugged space-borne laser transmitter prototype for the proposed space-borne Doppler winds Lidar. The objective for the laser transmitter is more than 20 W of average laser output power at 355 nm (see Table 3). The Raytheon-Fibertek laser transmitter prototype will be completed by November 2005. It is intended to serve as an engineering model for the Doppler winds LIDAR laser transmitter and to reduce the risk and cost of the proposed space-borne Doppler winds LIDAR demonstration mission. Raytheon plans to conduct extended testing with this prototype laser to demonstrate its performance and reliability. The development path followed by Raytheon & Fibertek parallels the approach adopted in the CALIPSO program to reduce the risks of future flight laser development.

Table 3: Threshold and Objective requirements for the Raytheon-Fibertek space prototype laser.

	Threshold Requirements	**Goal Requirements**
Type	Active Q-switch Diode-pumped Nd:YAG	Active Q-switch Diode-pumped Nd:YAG
Wavelength	Single Frequency:1064/355/308-320 nm	Single Frequency:1064/355/308-320 nm
Pulse Energy	700 mJ at 1064 nm	1 J at 1064 nm
THG Efficiency	45%	50-55%
PRF	50 Hz	100 Hz
Pulse Width	10-20 ns (50-100 MHz line width)	10-20 ns (50-100 MHz line width)
Spatial Mode	$TEM_{0,0}$	$TEM_{0,0}$
Divergence	≤ 0.5 mrad (1/e2 full-width)	≤ 0.3 mrad (1/e2 full-width)
Beam Quality	$M^2 < 2$	$M^2 < 1.3$
Cooling	Conductively cooled with interfaces for: (1) coolant circulation for ground testing (2) heat-pipes and radiators for space (upgrade path)	Conductively cooled with interfaces for: (1) coolant circulation for ground testing (2) heat-pipes and radiators for space (upgrade path)
Lifetime	3 yrs	5 yrs

4.3 Telescope Technology and Readiness

***<u>TRL Summary:</u>* 1-meter scanning telescope for Doppler winds LIDAR is at TRL 5. This assessment is based on the 1-meter telescope used in IceSat GLAS, 1-meter telescope for the CALIPSO LIDAR, and the 1.5-meter telescope for ADM-Aeolus ALADIN. Innovative scanning technologies are currently being developed at a number organizations including NASA Goddard Space Flight Center (GSFC), NASA Langley Research Center (LaRC) and Raytheon Space and Airborne Systems.**

The proposed direct-detection Doppler wind LIDAR baseline utilizes a 1-meter scanning telescope to meet system efficiency requirements and to perform eight observations for each scanning cycle. For direct-detection Doppler winds LIDAR, the telescope functions as a “photon bucket”. Therefore, the requirement on telescope surface quality is low compared to telescopes for coherent systems that must be diffraction limited. Technologies to design and fabricate 1-meter or larger telescopes are mature. The James Webb Space Telescope (JWST), which is being developed and is scheduled for launch in 2011, has a 6.5-meter diameter mirror. Both the IceSat GLAS, launched in January 2003, and CALIPSO, scheduled for launch in 2005, used a 1-meter beryllium mirror for their telescope. The ADM-Aeolus ALADIN will use a 1.5-meter SiC mirror. Therefore, we are confident that developing a 1-meter telescope mirror for the Doppler winds LIDAR is well within the current industrial capability.

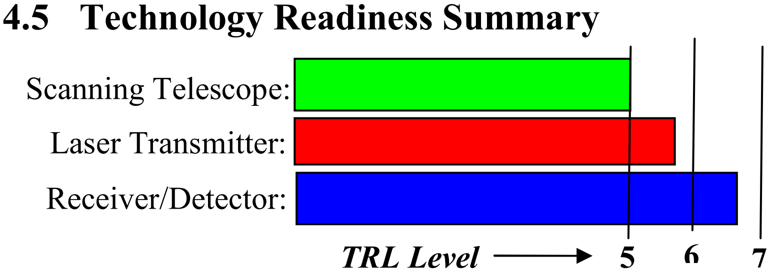
The challenge is to reduce the weight of the mirror and telescope so that scan-induced momentum to the spacecraft can be compensated. Doppler winds LIDAR requires step-and-stare scanning. The rapid acceleration and deceleration of a large telescope will transfer significant angular momentum to the spacecraft. It will also consume a significant amount of power. Reducing the telescope mass, while maintaining a stiff and rigid structure, will permit telescope motion with a short deceleration and damping times. Moreover, reducing the telescope weight will reduce the load on the scanning motor and lead to lower power requirements and a smaller thermal load. A promising technology to solve the momentum load and power requirements of a large scanning telescope is to use holographic or diffractive optical elements (HOE/DOE). This technology is currently being investigated at the NASA Goddard Space Flight Center (GSFC). An innovative implementation of the HOE/DOE concept using mature and space-qualified optical materials rather than dichromated gelatin (as used in NASA GSFC's HOE design) is being developed and demonstrated at Raytheon Space and Airborne Systems. We believe that the scanning telescope for the proposed Doppler winds LIDAR demonstration mission is currently at a TRL 5. We expect that the development and demonstration of the innovative implementation of the HOE with space-qualified materials at Raytheon will advance scanning telescope to TRL 6 in 2006-2007.

4.4 Receiver Technology and Readiness

<u>TRL Summary:</u> The TRL for a direct-detection Doppler winds LIDAR receiver is considered to be between 6-7. The justification for this is that several tunable Fabry-Perot etalons have been flown or will be flown on satellites in similar configurations to what would be required for a direct-detection Doppler winds LIDAR. A few examples are Dynamics Explorer 2, Visual Airglow Experiment flown on the Atmopsheric Explorer –C, -D & -E, HRDI, TIDI, GLAS, ADM-Aeolus ALADIN and CALIPSO.

Critical to the implementation of a satellite wind LIDAR instrument is the receiver/detector. For direct-detection Doppler wind LIDAR the receiver detects the small wavelength shifts in the backscattered laser light to measure winds. The heritage of Fabry-Perot based direct-detection Doppler wind receivers in space is extensive for passive neutral wind sounding and temperature sensing. The first Doppler wind imaging interferometer was flown in 1981 on the Dynamics Explorer Spacecraft. In 1991, the High-resolution Doppler Imager (HRDI) was flown on the Upper Atmosphere Research Satellite (UARS), which is still in operation today. A more recent example is the TIMED Doppler Interferometer (TIDI) launched by NASA in 2004. The TIDI instrument is based on a Fabry-Perot etalon that imaged multiple orders of interference onto a CCD camera combined with the Circle to LIne Optic (CLIO- U.S. Patent #4,893,003), which enabled high-spectral resolution of several atmospheric emission lines to measure wind velocities and temperatures from 60-300km. Scheduled to fly in October of 2007 is the ADM-Aeolus Atmospheric Laser Doppler Instrument *(ALADIN)*. ALADIN is a direct-detection LIDAR incorporating a fringe-imaging receiver for detecting aerosol and cloud backscatter and a double-edge receiver for detecting molecular backscatter. While many Fabry-Perot etalons have been flown in space, there are current technology development projects that are underway at NASA Goddard and MAC to advance this technology for future satellite missions. These developments include advanced control architectures and use of light weight composites. Since the overall efficiency of the receiver is important for a space wind LIDAR, technology developments to improve the Quantum Efficiency (QE) of detectors at 355 nm are also underway. ***In summary, the receiver subsystem for a direct-detection system is at a higher TRL level, of 6-7, compared to other subsystems.***

4.5 Technology Readiness Summary



5 Mission Cost Summary

Table 4 summarizes the estimated cost of a space-based direct-detection DWL as a stand-alone system; all amounts are in 2005 U.S. dollars. The instrument is expected to be reduced to about $90M if the direct-detection system is designed as part of a hybrid DWL, which is due to the elimination of the need for a custom CCD and reduced laser power requirement. As shown in Table 4, the total instrument cost is less than $100M. The cost for spacecraft, launch vehicle and support, and mission operation for 3 years is estimated to be $105M. We plan to budget $20M as mission management reserve. The total mission cost, including the $20M management reserve, is estimated to be $220M. The following sections provide cost basis for each of the cost categories. Since the first mission is intended to be a demonstration mission, potential descoping options include reducing mission life from 3 years to 2 years, which would lead to further reduction in total mission cost to about $200M.

Table 4: Approximate mission cost for a Doppler wind LIDAR satellite mission with direct detection only.

Laser Transmitter Subsystem	$18M
Scanning Telescope/Beam Delivery Subsystem	$12M
Receiver/Detector Subsystem	$15M
Instrument Design, Fabrication, Assembly	$30M
Integration and Test	$20M
Instrument Subtotal	**$95M**
Spacecraft	$50M
Launch & Support	$40M
Mission Operations & Management	$15M
Spacecraft, Launch and Operation Subtotal	**$105M**
Mission Management Reserve	$20M
Approximate Total Mission Cost	**$220M**

5.1 Laser Transmitter Cost

The development and space-qualification cost of the CALIPSO laser is about $8.5M. The laser transmitter required for the Doppler winds LIDAR system is at a higher power level than the CALIPSO laser transmitter. We estimate a cost scaling factor of 2X for the Doppler winds LIDAR transmitter relative to the CALIPSO laser transmitter. This implies an estimated cost of $17M for the winds LIDAR laser transmitter. Add $1M for nonlinear crystals (used in third harmonic generation) lifetime validation and test, we arrive at a total cost of $18M.

5.2 Scanning Telescope/ Beam Delivery Subsystem Cost

A risk reduction 1-meter scanning telescope prototype is currently being designed at Raytheon Space and Airborne Systems. Based on the prototype cost and cost of the 1-meter telescopes for the IceSat GLAS and CALIPSO, we estimate the cost of developing the scanning telescope subsystem for the DWL to be $10M. As discussed in the technology section, the telescope for a direct-detection DWL functions as a "photon bucket". This leads to fairly low telescope surface quality requirements, which in turn leads to lower cost. Beam delivery and alignment subsystems have been designed and developed for the GroundWinds and BalloonWinds programs. Even though they are not space-qualified, they provide credible references for the cost to develop a space-qualified version of the subsystem. Based on the cost for GroundWinds and BalloonWinds and space qualification cost, we estimate that the cost of developing the beam delivery and alignment subsystem for the space-based DWL is $2M.

5.3 Receiver/Detector Subsystem Cost

The cost for the receiver/detector subsystem cost is based on the TIDI interferometer, which included a single fringe imaging Fabry-Perot etalon and a CCD detector. The approximate total cost for the TIDI interferometer was $8M, our estimate of $15M includes provision for a custom high efficiency UV CCD design ($4M), and the implementation of a second Fabry-Perot etalon optimized for aerosol backscatter sensing ($3M). The $8M, based on TIDI, includes the cost of a space qualified clear air optimized Fabry-Perot channel. This estimate is justifiable since the design would be very similar to the TIDI interferometer. The custom CCD camera design includes provision for chip design, 2 chip prototype runs and full packaging and space qualification of the flight camera(s). While this cost estimate presumes the use of a CCD detector, it should be noted that the estimated cost for this component should be viewed as a maximum for any high efficiency detector required to meet instrument system requirements.

5.4 Instrument Design, Fabrication, and Assembly

Again, using GroundWinds, BalloonWinds, High-resolution Doppler Imager (HRDI) on NASA UARS, and CALIPSO as references, we estimate that the total cost for instrument design, fabrication, and assembly is about $30M. The design, fabrication, and assembly of the BalloonWinds DWL are about $3M. We apply a scaling factor of 10X to account for the complexity of space instrument development and space qualification.

5.5 Integration and Test

Significant efforts are needed to integrate and test the DWL due to the complexity of the instrument, high energy laser transmitter, and large telescope. Based on extensive experience with other space instruments integration and test (e.g. HRDI, MODIS, etc.), we estimate the total integration and test cost to be $20M.

5.6 Spacecraft, Launch and Support

Discussions with potential spacecraft vendors (e.g. Spectrum Astro Space Systems) indicate that the spacecraft for the proposed DWL will cost about $50M based a 3-year mission lifetime requirements. It is possible to reduce the spacecraft cost to $40M if mission lifetime is descoped to 2-years. Our baseline launch vehicle is Taurus. It has 3,100 lb launch load capability, which is enough to launch the proposed DWL into the intended 350-400 km sun synchronous low Earth orbit (LEO). Based on standard launch cost estimates from NASA and DOD, $40M is budgeted for launch and support.

5.7 Mission Operations & Management Reserve

Based on the proposed 3-year mission lifetime, we estimate that mission operation will cost about $5M per year for a total cost of $15M. For a 2-year mission, the cost will be about $10M. In order to ensure mission success, we include $20M (about 10% of the baseline mission cost) as Mission Management Reserve in our mission cost estimate.