# Compact, Engineered, 2-Micron Coherent Doppler Wind Lidar Prototype: A New NASA Instrument Incubator Program Project

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## Abstract

A new project, selected in 2005 by NASA's Science Mission Directorate (SMD) under the Instrument Incubator Program (IIP), will be described. The 3-year effort is intended to design, fabricate, and demonstrate a packaged, rugged, compact, space-qualifiable coherent Doppler wind lidar (DWL) transceiver capable of future validation in an aircraft and/or Unmanned Aerial Vehicle (UAV). The packaged DWL will utilize the numerous advances in pulsed, solid-state, 2-micron laser technology at NASA's Langley Research Center (LaRC) in such areas as crystal composition, architecture, efficiency, cooling techniques, pulse energy, and beam quality. The extensive experience of Raytheon Space and Airborne Systems (RSAS) in coherent lidar systems, in space-based sensors, and in packaging rugged lidar systems will be applied to this project. The packaged transceiver will be as close to an envisioned space-based DWL system as the resources and technology readiness allow. We will attempt to facilitate a future upgrade to a coherent lidar system capable of simultaneous wind and $CO_2$ concentration profile measurements. Since aerosol and dust concentration is also available from the lidar signal, the potential for a triple measurement lidar system is attractive for both Earth and Mars remote sensing. A key follow on step after the IIP will be to add a telescope, scanner, and software for aircraft validation. This IIP should also put us in a position to begin a parallel formulation study in the 2006-2007 timeframe for a space-based DWL demonstration mission early next decade.

## The Need for Tropospheric Winds

The science and operational communities of the United States (US) and other countries greatly need global profiles of wind velocity for many applications; especially improved weather prediction, greater understanding of climate issues, and mitigation of weather hazards to the population and to commerce. The high value of winds to improved weather prediction is highlighted by the fact that it is ranked as the highest priority unmet measurement by the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO), which is a joint office representing the US Department of Defense (DOD), the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA)[1]. A strong case for tropospheric wind profiling from space has been made in the scientific literature[2-6]. It has also been shown to have a very positive economic benefit to the country, even when only considering the benefit of fuel savings[7-8]. The wind measurement requirements, in order for the wind observations to be useful through assimilation into computer models, were defined in 2001 by a scientific panel led by NASA and NOAA[9-12]. “Threshold” and “Objective” requirements were listed and were stated to provide a “noticeable” and “significant” improvement, respectively. Meeting these wind measurement requirements from Earth orbit, especially the coverage, resolution, velocity error, and number of simultaneous tracks of horizontal vector wind, is a challenge. These requirements will not all be met simultaneously by any existing or currently planned sensing systems[11].

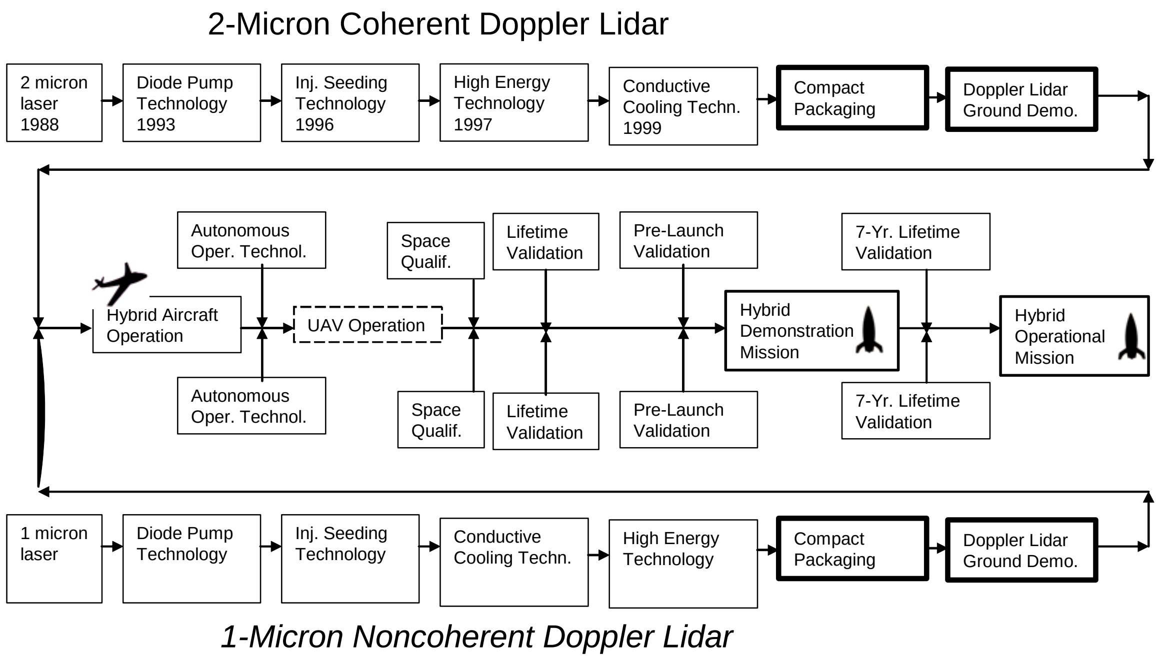
## The Technology Solution

The consensus of NASA and NOAA is that the desired vector horizontal wind profile measurements can best be made by a <u>hybrid</u>, pulsed, DWL system; that is, a lidar system consisting of <u>both</u> a coherent (heterodyne) detection DWL system and a noncoherent (direct) detection DWL system working together in a complementary fashion[13]. The coherent DWL would make highly accurate wind profile measurements in atmospheric regions having an aerosol backscatter coefficient above a certain threshold, and in areas with clouds. The noncoherent DWL would make less accurate wind measurements, and would require a larger receiver mirror and higher pulsed laser optical power (pulse energy-pulse rate product), but would obtain data from molecular backscatter in the mid- and upper-troposphere where there are fewer aerosols. Both the coherent and noncoherent Doppler wind lidar technologies have been steadily advanced and demonstrated, and a key milestone would be a space demonstration of vector wind measurement in the near future.

The European Space Agency (ESA) is developing a space demonstration of a noncoherent DWL for launch in 2008, the Atmospherics Dynamics Mission (ADM)[14]. For reasons of cost, risk, and spacecraft accommodations, the DWL will not scan and will therefore not measure horizontal vector winds. Nevertheless, it will provide very valuable information about the performance of the noncoherent DWL technology, and about the atmosphere. Perhaps the information gained about the atmosphere will allow a relaxation of the wind measurement requirements, leading to more mission design options. For now, the US NASA/NOAA requirements require vector winds to be measured at multiple cross-track distances from the spacecraft ground track. This requirement mandates a step-stare lidar scanner that is at least capable of multiple look directions lying on the surface of a cone centered about the nadir direction. It would be prudent to demonstrate space-based, scanning, vector wind profile measurements with both coherent and noncoherent DWL’s.

## Roadmap to a Space Demonstration Mission

A possible roadmap to a Doppler wind lidar space demonstration mission, and beyond to an operational mission is shown in the figure. Two parallel paths are shown for the development of the




coherent and noncoherent technologies and lidar systems. Many of the required steps shown have already been accomplished. Other critical work that has been done in the past, that enables this roadmap and is not shown in the figure, includes theoretical development; computer performance simulation; characterization of the atmosphere; observing system simulation experiments (OSSEs); lidar intercomparisons; aircraft flight campaigns (coherent); 1-micron space lidar altimetry missions (noncoherent); telescope, scanner, and receiver development; and pump laser diode array characterization, lifetime, and improvement efforts. The work to be performed under the recently awarded IIP project is indicated by the heavy shaded boxes in the coherent lidar path. Our IIP project will compactly package the LaRC pulsed 2-micron laser technology, and demonstrate the packaged, rugged transceiver through ground-based measurements. The corresponding heavy shaded boxes in the noncoherent path indicate the companion IIP project that will be performed at NASA's Goddard Space Flight Center (GSFC) using noncoherent DWL technology. That project intends to perform some aircraft flights, also. These paths are shown to merge for the highly recommended step of flying in a high-altitude aircraft to mimic the downward view through clouds from space, to see how the two lidar technologies work together, and to gain experience with the interaction of the technologies in both DWL systems. The roadmap shows a possible UAV demonstration. The dashed box indicates that it is optional. Work should begin as soon as possible on autonomous operation of the DWL systems, lifetime validation, space qualification, and pre-launch validation of both photon sensitivity and Doppler shift calibration. Following this, a space-based demonstration of a scanning DWL collecting vector winds is recommended. Ideally, this would be a hybrid DWL demonstration, but it could also consist of separate demonstrations of coherent and noncoherent DWL systems. The final goal is an operational mission employing a hybrid DWL. Due to range squared losses for all lidar remote sensing, the orbit height should be as low as possible; perhaps 400 km.

## Additional Applications of the Technology

There have been two interesting developments recently that add more applications beyond wind measurement for the pulsed 2-micron laser technology. First, measurement of $CO_2$ concentration globally has become very important for climate change understanding. In principle, using the differential absorption lidar (DIAL) technique, the 2-micron laser can simultaneously measure wind and $CO_2$ from earth orbit[15]. Furthermore, the laser can emit double pulses with one pulse of each DIAL wavelength, leading to higher concentration accuracy. This had been demonstrated by us on the ground[16-17]. Second, the US goal to explore Mars has led to a need for landing more mass on Mars surface with much greater location accuracy. This leads to a requirement for better characterization of the Mars atmosphere. The 2-micron laser technology is capable of providing wind, dust, and air density profiles from Mars orbit[15]. The air density would be derived from DIAL measurements of the $CO_2$ concentration, the primary component of the atmosphere.

## References


1. "Unaccommodated Environmental Data Records," National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office, p. 4 (April 1996)
2. R. Atlas, E. Kalnay, and M. Halem, "Impact of satellite temperature sounding and wind data on numerical weather prediction," Opt. Engr. 24, 341-346 (1985)
3. G. D. Rohaly and T. N. Krishnamurti, "An Observing System Simulation Experiment for the Laser Atmospheric Wind Sounder (LAWS)," J. Appl. Meteorol. 32, 1453-1471 (1993)
4. W. E. Baker, et al, "Lidar-measured winds from space: A key component for weather and climate prediction," Bull. Amer. Meteor. Soc. 76, 869-888 (1995).
5. R. Atlas, "Experiments to determine the requirements for lidar wind profile data from space," Proc. SPIE 3429, 79-89 (1998)
6. R. Atlas, G. D. Emmitt, J. Terry, E. Brin, J. Ardizzone, J. C. Jusem, and D. Bungato, "Potential impact of space-based lidar wind profiles on weather prediction," Proc. SPIE 5154, 74 (2003)
7. J. J. Cordes, "Economic Benefits and Costs of Developing and Deploying a Space-Based Wind Lidar," Dept. of Economics, George Washington University, D-9502 (Mar. 1995)
8. J. J. Cordes, "Projected Benefits in Military Fuel Savings from Lidar," Dept. of Economics, George Washington University (June 1998)
9. M. J. Kavaya, G. D. Emmitt, R. G. Frehlich, F. Amzajerdian, and U. N. Singh, "A Space-Based Point Design for Global Coherent Doppler Wind Lidar Profiling Matched to the Recent NASA/NOAA Draft Science Requirements," Digest of the 21st International Laser Radar Conference, p. 817, Quebec City, Quebec, Canada (8-12 July 2002)
10. J. Wang, M. Dehring, C. Nardell, D. Dykeman, and B. Moore III, "Direct Detection Doppler Wind Lidar: Ground-based Operation to Space," Proc. SPIE 5154, 93 (2003)
11. M. J. Kavaya, U. N. Singh, F. Amzajerdian, G. J. Koch, and J. Yu, "Improved Weather Prediction, Climate Understanding, and Weather Hazard Mitigation through Global Profiling of Horizontal Winds with a Pulsed Doppler Lidar System," Concept Paper Submitted to the National Research Council (NRC) Space Studies Board (SSB) (16 May 2005)
12. See also these links for the wind requirements at http://space.hsv.usra.edu/LWG/Index.html and at http://www.swa.com/ALD/LidarProducts/targetAtm/ . Ref. 11 has corrected some errata.
13. M. Hardesty, W. Baker, G. D. Emmitt, B. Gentry, I. Guch, M. Kavaya, S. Mango, K. Miller, G. Schwemmer, and J. Yoe, "Providing Global Wind Profiles – The Missing Link in Today's Observing System," Concept Paper Submitted to the National Research Council (NRC) Space Studies Board (SSB) (16 May 2005)
14. A. Stoffelen et al, "The Atmospherics Dynamics Mission for Global Wind Field Measurement," Bull. Amer. Meteorol. Soc., 73 (Jan. 2005)
15. U. N. Singh, G. J. Koch, M. J. Kavaya, F. Amzajerdian, and S. Ismail, "A Proposal to Simultaneously Profile Wind and $CO_2$ on Earth or Mars with 2-μm Pulsed Lidar Technologies," 13th Coherent Laser Radar Conference, Kamakura, Japan (16-21 Oct. 2005)
16. J. Yu, A. Braud, and M. Petros, "600-mJ, double-pulse 2-micron laser," Opt. Lett. 28, 540 (2003)
17. G. J. Koch, B. W. Barnes, M. Petros, J. Y. Beyon, F. Amzajerdian, J. Yu, Davis, S. Ismail, S. Vay, M. J. Kavaya, and U. N. Singh, "Coherent Differential Absorption Lidar Measurements of $CO_2$," Applied Optics 43(26), 5092-5099 (2004)