Integrating a Doppler Wind Lidar into a network of wind observing systems: capitalizing on synergisms with a high precision, cloud scene penetrating lidar

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Executive Summary

This white paper discusses both the advances in DWL since the 2007 Decadal Survey and the continued need for global 3D wind observations. To meet this need, we argue for an initial pathfinder/survey mission that recognizes the preponderance and impact of clouds and favors high precision/representativeness over global coverage. The suggestions offered here are, in part, a response to NASA's recent recommendation "**It is important to avoid all or nothing strategies for the three-dimensional wind vector measurements, as important progress is possible with less than comprehensive observing strategies**."

This white paper from NASA LaRC is guided, in part, by decades of discussions/deliberations within the NASA/NOAA funded Working Group on Space-based Lidar Winds and the following three assertions:

a) No single technology is likely to deliver, at a reasonable cost, full tropospheric/lower stratospheric wind profiles at the horizontal/vertical coverage and precision desired by the communities associated with the Earth System Science Themes;
b) Capitalization on synergisms between a DWL and existing or promising future wind observing systems is key to optimizing the Nation's investment in enhancing the collection of global wind data for both the research and operational communities;
c) It is highly desirable to seek international and/or private sector partnerships to achieve the most cost effective DWL space missions.

NASA has invested in both direct detection and coherent detection DWL technologies over the past decade. This white paper focuses on the coherent detection and its long use (since 1972) in ground based and airborne research and applications. Reservations expressed by the 2007 NRC reviewers on the technology's readiness for a mission have been addressed and new modest energy per pulse, high pulse rate lasers have been designed and prototyped for space-based DWL applications.

1. Introduction

This white paper is prepared with awareness of other similar white papers addressing the need for global wind observations essential for operational weather forecasting on all scales and at all latitudes. (Table 1). The general call for global 3D winds was well documented in the last Decadal Survey [NRC, 2007] and the need remains just as strong today if we are to realize the "transformational" advances in NWP and climate modeling discussed in published papers such as Baker, et al, 2014. The following recommendation was recently made in NASA's Workshop Report on Scientific Challenges and Opportunities in the NASA Weather Focus Area [NASA, 2015]:

"Global measurements of the spatiotemporal (four-dimensional) evolution of large-scale horizontal wind vectors are urgently needed. **It is important to avoid all or nothing strategies for**

the three-dimensional wind vector measurements, as important progress is possible with less than comprehensive observing strategies. Some additional trade studies may still be needed to design the most cost-effective strategy for wind measurements (based on lidar, radar, and atmospheric motion vectors) from satellites and airborne flights."

NASA has been working to enable global wind measurements from earth orbiting platforms for several decades. Doppler lidar technology has advanced to the point where scientifically useful wind measurements can be made from space [Baker et al., 2014]. The primary, but not only, societal benefits from such measurements would be improved severe weather warnings and general weather forecasting.

NASA's efforts over the past ten years have included the following: technology development, ground-based and airborne technology validation, wind measurement requirements definition, OSSEs, and space mission design. Table 2 provides a summary of the most important advances in coherent DWL relevant technology over the last decade while Table 3 lists nine formal evaluations of proposed space mission designs conducted since 2001.

In 2007, the NRC endorsed the hybrid Doppler lidar (HDWL) concept previously selected by NASA and NOAA jointly [NRC, 2007]. The general definition of a hybrid DWL [Emmitt, 2001] states that the aerosols and molecular backscattered signals be assigned to different optical detection methods. Both the ADM and OAWL wind lidar concepts use direct detection for aerosol and/or molecular backscatter. However, the HDWL involves a coherent-detection Doppler lidar using backscatter from natural aerosol particles and a direct-detection Doppler lidar using backscatter from molecules. The status of NASA's DWL efforts as of 2015 was recently presented in white papers at the annual Coordination Group for Meteorological Satellites (CGMS) conference [Wu and Kavaya, 2013; Wu et al, 2015].

Just as is the case with temperature, moisture, aerosols and clouds, **wind observations will undoubtedly continue to be obtained via multiple technologies.** There are numerous road maps for DWL global winds that tend to be single technology centric. This white paper recognizes the role of several technologies to provide wind observations and is guided by the decades of discussions within the NASA/NOAA funded WGSBLW and the following <u>three key assertions</u>:

a) No single technology or mission design can deliver full troposphere/lower stratospheric wind profiles at the horizontal/vertical coverage and precision desired by the communities associated with the Earth System Science Themes;
b) Capitalization on <u>synergisms</u> between a DWL and existing or promising future wind observing systems is <u>key</u> to optimizing the Nation's investment in enhancing the collection of global wind data for both the research and operational communities;
c) It is highly desirable to seek international and/or private sector <u>partners</u> in projects to achieve the most cost effective DWL space missions.

We argue that **the first full horizontal vector (bi-perspective) DWL mission on the path to global coverage (horizontal and vertical) should not compromise precision for coverage.** Furthermore, the first bi perspective DWL mission should be a <u>pathfinder or survey mission</u> which builds upon, as much as possible, existing technology, algorithm maturity, and airborne experience with earthward perspectives (particularly over water).

While recognizing the upper atmosphere advantages of direct detection DWL technologies (e.g. ADM, OAWL, TWiLITE) in meeting the NWP needs, NASA **<u>LaRC argues for a pathfinder/survey mission using the intrinsically high precision and long airborne heritage coherent detection.</u>** It is further argued that a mission using coherent detection will yield equal performance in day and night and will allow for precision and vertical resolution in the PBL and in partly cloudy scenes. <u>This mission will also provide valuable input to setting requirements for any future DWL technology (coherent or direct detection) selected for follow-on missions to fill in documented critical observation gaps.</u>

2. Science and Application Target

As discussed in Section 1, the general Science and Application target is improved measurement and analysis of the 3-D global wind field. A pathfinder mission that is both exploratory (experimental sampling modes) and frequently available for operational NWP is highly desired for a spacebased bi-perspective measurement of the winds that has no space heritage. A few examples of a pathfinder mission's contributions to the science objectives are:

- Optimize synergisms between a highly precise DWL and existing or planned wind observing systems (e.g. scatterometers, hyperspectral imagers, constellations of passive imagers and rawinsondes);
- Provide direct measures of the depth of most PBLs to be used in NWP model validation;
- Provide wind observations above, within, and below clouds with off nadir perspectives in partly cloudy scenes ; Establish performance statistics in partly cloudy scenes for use in defining requirements for follow-on missions.
- Validate numerical model winds, especially in areas where several NWP models disagree;
- Provide line-of-sight DWL observations for NWP data assimilation evaluation of cloudy scene DWL observations.
- Provide wind observations for use in atmospheric weather reanalyses;
- Provide a pathway to composites and climatologies of low level moisture jets, upper level dust laden jets and sub-visual cirrus layers.

2.1 Description of Science and Application Targets and their importance to Earth System Science Themes

While numerical weather and climate models continue to improve in spatial/temporal resolution and in the extraction of useful information from available geophysical observations, the dearth of global measurements of winds remains a major impediment to improving our understanding of many elements associated with the Earth System Science Themes. Table 4 provides a summary of the potential advances to the individual Themes to be made by the pathfinder/survey mission discussed in this white paper.

As stated by NASA (http://science.nasa.gov/earth-science/focus-areas/earth-weather/), "Wind Lidar Science includes the studies that will aid the development of Three-Dimensional Tropospheric Winds from Space-based Lidars (3D-Winds). Measurement of global wind profiles is recognized as a primary unmet observational requirement for improving weather forecasts by the WMO and many international operational weather agencies. The wind field plays a unique dynamical role in forcing the mass field to adjust to it at all scales in the tropics, and at smaller scales in the extratropics. Direct observation of the global wind field would be extremely valuable for numerical weather prediction, as well as scientific diagnostics of large-scale atmospheric transport, weather systems, and boundary layer dynamics in Earth's atmosphere".

While contributions from satellite derived AMVs, inferred from cloud and water vapor motions, and surface winds (such as ASCAT and future CYGNSS), inferred from water surface roughness, have improved and increased data density greatly over the last 25 years, they only provide single level or layer winds. As a result, full profile global wind observations that can depict shear, boundary layer processes and transports continue to be limited primarily to ground launched rawinsondes and a few commercial aircraft soundings. Vertical profilers are still desperately needed by the observational and NWP communities, particularly in data sparse regions such as the Southern Hemisphere, the Tropics, and Polar Regions. This lack of data in these regions, and the imbalances with most of the Northern Hemisphere data coverage, significantly impacts global forecasts and remains a key concern (WMO 2016)

2.2 Utility of Measured Geophysical Variable to Achieve Science and Application Targets

Data impact assessments for currently available wind observations persistently show that the wind data have a high-ranking impact per observation on NWP metrics. One way of computing observation impacts is by using the adjoint of the model atmospheric data assimilation system (Gelaro et al., 2010). This method simultaneously estimates the impacts of individual observations on a selected measure of forecast error with respect to the verifying analysis from the surface to 1 hPa in terms of moist total energy (J/kg). Observation impacts on the GEOS-5 global model are computed once each day for the 24-h forecast initialized at 00z and are provided at http://gmao.gsfc.nasa.gov/products/forecasts/systems/fp/obs_impact/#. A monthly averaged example of these impacts where **negative** values of observation impact indicate that assimilation of a given set of observations has **improved** the 24-h forecast, are provides in Figures 1 & 2 illustrate the significant impact of various sources of wind observations on the global forecast. Note the high impact /observation of wind soundings as opposed to single layer winds.

As illustrated in Table 4, OSSEs for proposed observation concepts based upon various instrument and mission scenarios (GTWS, LAWS, GWOS, DWL-HYBRID, OAWL) predict measureable and significant (sometimes referred to as transformational) improvements in the Earth System Science themes. This is especially true in NWP forecasts (Theme II) and, by inference, reanalyses (Themes II and IV), climate modeling (Theme IV), global atmospheric water budgets (Theme I), ecosystem responses to changing wind borne inputs (Theme III) and wind driven desert migration with global redistribution of mineral laden dusts.

2.3 Measurement Quality Requirements Needed for Achieving the Science and Application Targets

The data requirements for global winds have evolved over the past few decades as NWP models improve in resolution, data assimilation and ensemble techniques. As mentioned above, OSEs and OSSEs provide guidance as to what the incremental impact might be for a totally new wind observing system or an improved current technology (e.g. scatterometers and hyperspectral imaging). Regarding the accuracy of 3D wind measurements (including representativeness), recent OSSEs have suggested a threshold of 3 m/s random error per horizontal component in the mid and upper troposphere and a maximum systematic bias less than 0.5 m/s. From a NWP perspective, each observation must be evaluated via a cost function that gives weight to observations based upon their precision and representativeness. Observations must also compete with the model's first guess and background errors. Thus, horizontal coverage (swath width), vertical coverage (clouds or aerosols permitting) and measurement quality all combine in a complex fashion to obtain a measureable impact on NWP and the expected cost/benefit to society.

The phrase "clouds permitting" represents a vagueness in expectations of an optical remote sensor's performance for layers above, within and below clouds. Based upon studies of LITE (Winker and Emmitt (1997)), GLAS (SWA (2006)) and CALIPSO (Emmitt et al., 2012), the probability of a single lidar shot intercepting clouds ($\tau > 0.1$) is > 50% globally. For 5 km segments, the probability of a cloud intercept is ~ 70 -75%. Current direct detection DWLs (e.g. ADM) are designed to integrate shots over ~100 km distances where the probability of a cloud within the integrated scene goes up to ~ 88%. Another finding from analyses of the CALIPSO data is that 79% of the time an 80 km flight segment contains at least 10% cloud free lines of sight into the PBL. A question that has not been addressed by the three nadir viewing systems mentioned above is how often and how useful are two off nadir (30-45 degrees) perspectives obtained within partly cloudy scenes. This basic question would be answered with a pathfinder mission.

2.4 Technology Readiness and Likelihood of Affordably Achieving the Required Measurements in the Decadal Timeframe

Here we envisage a global wind observing concept that is based on a mature DWL technology and ideal for a pathfinder mission.. While it is not certain at this time what the "end game" will be for DWL global winds, we argue for an approach that integrates a highly precise coherent DWL into a multi-platform, multi-perspective, multi-sensor network of wind measurement systems. This design will capitalize directly upon precise DWL observations as well as their synergisms with other wind observations (e.g. CMV height assignments, CMV and OVW point wind vector calibrations and removal of OVW directional ambiguities). Our recommended pathfinder /survey DWL space mission using coherent detection builds on decades of aircraft flight experience and on the knowledge gained from nine formal space mission instrument and mission studies listed in Table 3, of which six involved the pulsed, 2-micron, eyesafe, coherent detection, wind lidar technique. Coherent detection is attractive for wind measurement since it provides:

1) An accurate and low bias wind estimate whenever signal is above a threshold SNR,
2) Immunity from background light for equal day/night operation,
3) High photon efficiency from the background light immunity and the fundamental frequency estimation rather than intensity estimation,
4) Additional data products and coverage enhancement from preservation of the complete return signal spectrum, and
5) Data processing flexibility trading resolution with backscatter sensitivity with contextual velocity search narrowing.

Three epochs of the space based DWL approach are shown in Table 5. Winds have been measured with airborne-pulsed coherent lidar almost continuously since 1972, with 1993 marking the first flights with 2-micron lasers. NASA LaRC has been and continues to develop 2-micron lasers to permit the coherent wind lidar to go to space. Following the 2007 Decadal Survey, LaRC built a 2-micron coherent airborne lidar (DAWN) using a 250 mJ, 10 Hz laser which first flew in 2010 [Kavaya et al, 2014].

Early space wind mission concepts favored higher pulse energies for coherent wind lidar since aerosol backscatter sensitivity is improved proportionally with pulse energy multiplied by square root of pulse rate (not the laser average power). However, space mission simulations have revealed the large effect of clouds on mission performance. A higher pulse rate laser would increase the probability of some laser shots penetrating the porosity of the partly cloudy scenes and would lower the representativeness error of the wind measurement for assimilation in NWP models. We propose utilizing the recently Langley-developed higher pulse rate 2-micron laser that was initially designed for measurement of carbon dioxide column content. The new laser operating at 0.04 J and 200 Hz preserves approximately the same aerosol sensitivity as using a 250 mJ, 10 Hz laser, which was shown adequate in mission design studies.

We offer a path to affordable pathfinder and operational wind missions utilizing international collaboration. The proposed first pathfinder DWL mission uses only coherent detection wind lidar for horizontal wind measurements from the ISS JEM EF. The key to lowering NASA’s cost on the pathfinder and later operational missions is to partner with other countries and space agencies, using the strengths of each partner in a synergistic, efficient collaboration. ESA and European industrial partners have spent the last 15 years developing a direct-detection, UV, 1.5-meter telescope, molecular/aerosol DWL (ADM) for space, overcoming many technology hurdles, that is now planned for launch in 2017.

Given this development, ESA is now far ahead of NASA in the molecular DWL technology. It will be very cost effective for NASA to use its unique strength in 2-micron coherent aerosol DWL technology; perhaps flying in formation with ESA’s UV direct molecular DWL satellites for complete troposphere/lower stratosphere wind measurement coverage.

NASA could also benefit by partnering with Japan/JAXA and India/ISRO. JAXA, working with agencies such as NICT and NIES, has been developing 2-micron coherent wind lidar for the last 20 years. JAXA and their industries have indicated a willingness to collaborate with NASA on a 2-micron aerosol DWL mission. In India, both ISRO and the MOES have indicated a desire to work with NASA on a 2-micron coherent DWL mission. Although India does not have the laser or lidar technology, they have very advanced launch and spacecraft capabilities. We propose this international approach to affording the operational hybrid full troposphere DWL mission. The collaboration of NASA, JAXA, ISRO, and ESA will also bring together their respective science communities. The result will be significantly lower cost to NASA and the long-desired and currently lacking global wind measurements.

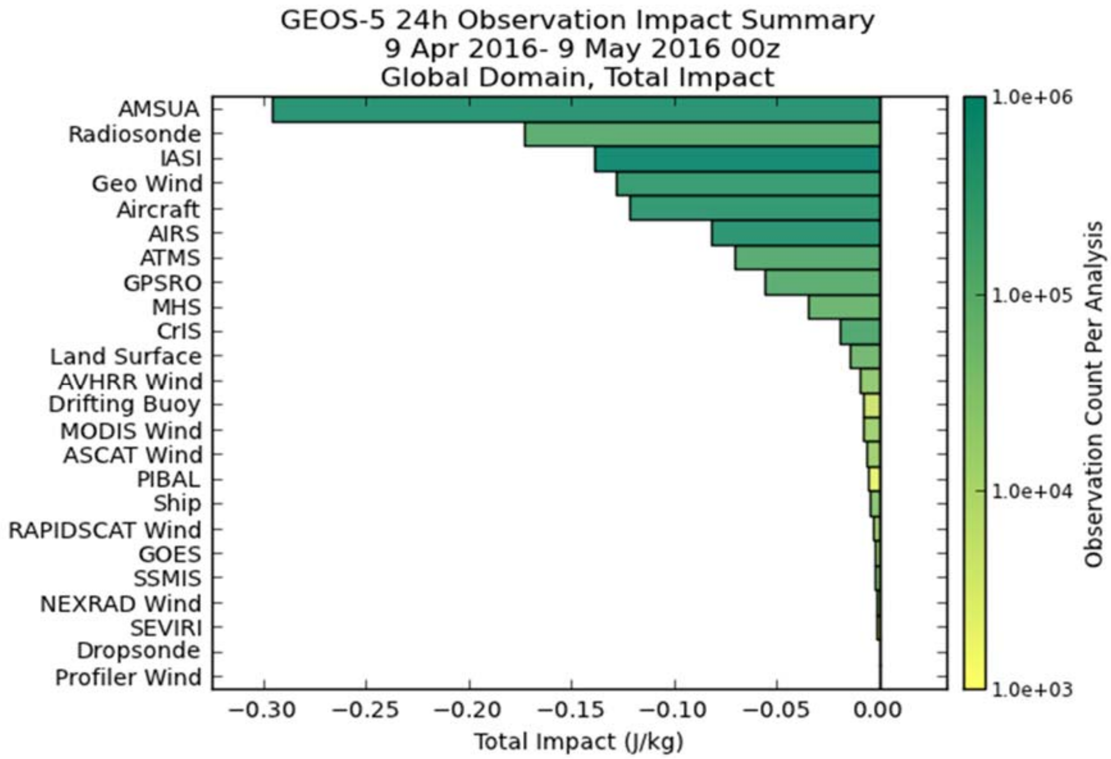

Figure 1: Total observation impact on the GEOS-5 24 hr forecast (valid at 00z) over the global domain during the period of 04/09/2016 to 05/09/2016.

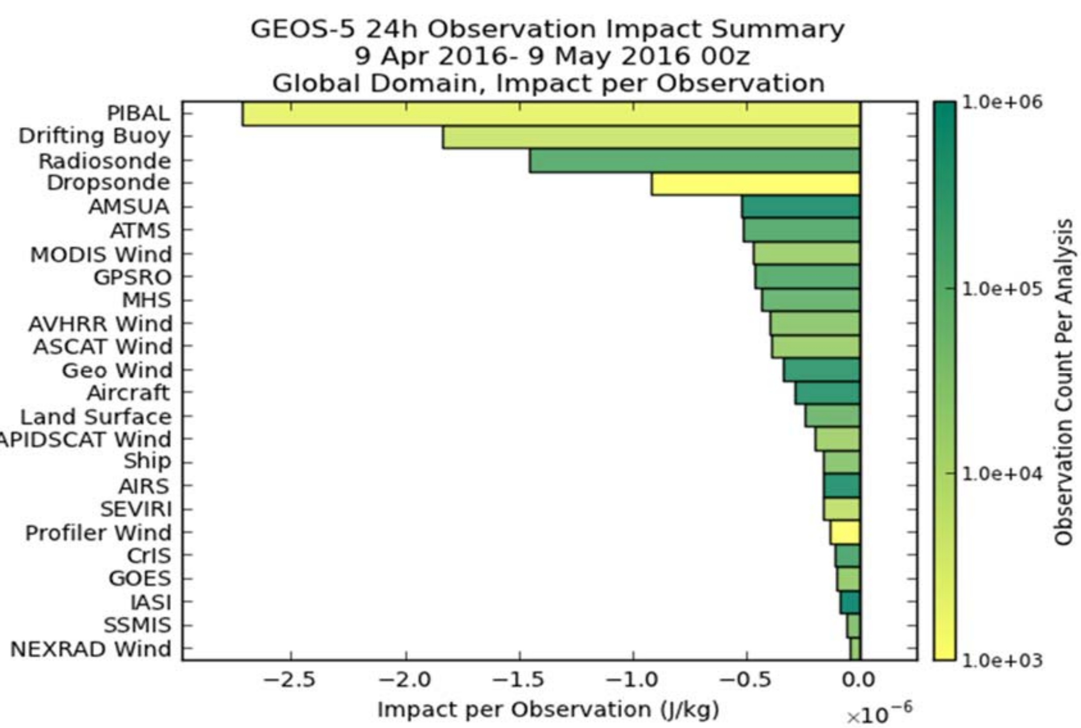

Figure 2: Impact per observation on the GEOS-5 24 hr forecast (valid at 00z) over the global domain during the period of 04/09/2016 to 05/09/2016.

Table 1. Calls for Global Winds from Earth Orbit			
Organi-zation	**Date**	**Quotation/Summary**	**Document**
WMO	2016	25 entries for "wind, horizontal" [includes 7 for NWP, 6 for Climate, 7 of those 13 for troposphere]	OSCAR Observation Requirements Data Base
NASA	2015	"The urgently needed observations that representatives mentioned most frequently were high (temporal and spatial) resolution wind profiles (explicitly mentioned in 13 slides)"; "Weather as a societal benefit area is strongly coupled to climate, the water cycle, and energy"	"Workshop Report on Scientific Challenges and Opportunities in the NASA Weather Focus Area,"
NASA	2011	"Strategic Goal 2: Expand scientific understanding of the Earth and the universe in which we live. Objective 2.1.2: Enable improved predictive capability for weather and extreme weather events. Objective 2.1.5: Improve understanding of the roles of the ocean, atmosphere, land and ice in the climate system and improve predictive capability for its future evolution."	2011 NASA Strategic Plan
WMO	2008	"Observations of upper winds are essential for operational weather forecasting on all scales and at all latitudes, …"	Guide to Meteorological Instruments and Methods of Observation," 7th ed., WMO-No. 8
DOD/ **Navy/ Director**	2007	"Among the 15 recommended missions, the measurement of global tropospheric winds is of significant interest to the Navy."	Aug. 8, 2007 Letter from Technical Director, Oceanographer of the Navy to NASA SMD AA (Stern)
NRC	2007	One of 15 recommended NASA earth science missions. Will contribute to Societal Challenges: Extreme Event Warnings, Human Health, Improved Weather Prediction, and Air Quality.	"Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," "Earth Science Decadal Survey"
NASA	2006	NASA also is working to advance radar, laser, and light detection and ranging technologies to enable monitoring of such key Earth system parameters as land surface, oceans, ice sheet topography, and global tropospheric winds that could lead to advances in weather and severe storm prediction.	2006 NASA Strategic Plan
NSTC/ **CENR/ IWGEO**	2005	"For example, high-resolution lower-atmosphere global wind measurements from a spaceborne optical sensor would dramatically improve a critical input for global prediction models, improving long-term weather forecasting." Highest importance ranking for improved weather forecasting, disasters, oceans, climate….	NSTC, Committee on Environment and Natural Resources, Interagency Working Group on Earth Observations, "Strategic Plan for the U.S. Integrated Earth Observation System,"
ESA	1999	"… improvement in analyzing global climate, its variability, predictability and change requires measurements of winds throughout the atmosphere."	"Reports for Mission Selection. The Four Candidate Earth Explorer Core Missions. Atmospheric Dynamics Mission," SP-1233 (4)]
NPOESS	1996	"Direct tropospheric wind measurements would provide a greater impact on numerical weather prediction than any other new space-based observation."	"Unaccommodated Environmental Data Records: Technology Status and Promising Technological Areas"

Table 2. Coherent DWL Relevant Technology Advances in Last Decade		
Year	**Advance**	**Significance**
2003	GSFC ICESAT/GLAS demonstrates 7 microradians laser pointing knowledge	Order of magnitude better than required for coherent DWL
2005	Langley demonstrated 1.2 J 2-micron pulse energy	Factor of 4.8 greater than space mission requirement of 0.25 J
2010	Langley completed 0.25 J, 10 Hz, 2-micron airborne coherent DWL "DAWN"	Airborne demonstration beyond space mission requirement of 0.25 J, 5 Hz
2010 – 2015	DAWN completed five airborne campaigns including NASA GRIP and NASA Polar Winds	Important aircraft experience; several lessons learned
2015	During Polar Winds Iceland, joint flights of DAWN with one other coherent and two other direct airborne Doppler wind lidar systems	Rare opportunity to compare wind profiles from four Doppler lidar systems for better performance estimation
2015	Langley demonstrated next generation 2-micron laser: 1 End pumping replaces side pumping 2 Square lasing crystal replaces cylindrical 3 Pump at 1940 nm replaces 792 nm 4 200 Hz laser pulse rate replaces 5 Hz while preserving coherent lidar laser FOM	1 Matching pump to lasing volume increases laser efficiency 2 Heat removal from 100% of flat surface much easier than from <50% of curved surface 3 Much lower quantum defect deposits less waste heat in crystal Combination of 1, 2, 3 dramatically reduces waste heat in crystal; thereby improving beam quality for coherent detection 4 For space mission, much higher probability of cloud porosity penetration, decreased representativeness error; retaining same aerosol backscatter sensitivity
2012	GSFC Instrument Design Center study showed two 70-cm diameter telescopes in ISS Japanese Experiment Module Exposed Facility (JEM EF) allowed volume	Increase from earlier 50 cm to 70 cm doubles aerosol backscatter sensitivity of mission
2015	NASA CATS lidar mission successful from ISS JEM EF	First pulsed lidar mission on ISS JEM EF

Table 3. Engineering Design Studies at Goddard Integrated Design Center (IDC) for Global Winds from Earth Orbit

Date	Study Type	Lidar Type	Notes
Sept. 2001	Instrument	Molecular, 0.355 microns	GTWS 400 km SSO
Oct. 2001	Mission		
Feb. 2002	Instrument	Aerosol, 2 microns	
Feb. 2002	Mission		
Sept. 2006	Instrument	Molecular, 0.355 microns & Aerosol, 2 microns	GWOS 400 km SSO
Oct. 2006	Mission		
Feb. 2008	Instrument	Molecular, 0.355 microns & Aerosol, 2 microns	NWOS SSO
Dec. 2010 – Jan. 2011	Instrument	Molecular, 0.355 microns & Aerosol, 2 microns	WISSCR, ISS 350-400 km, EO
June 2012	Instrument	Aerosol, 0.355 microns (shared laser with molecular system)	OAWL, ISS 350-400 km, EO

Table 4. Advancement in Understanding from Science Target

Earth System Science Theme	Areas of advancement with DWL full tropospheric soundings
Theme I –Global Hydrological Cycles and Water Resources	Water vapor transport and hydrological cycle studies Global moisture budget studies Impacts on river and flood forecasts
Theme II –Weather and Air Quality: Minutes to Sub seasonal	Numerical Weather Prediction Weather and Air Quality forecasting Severe Weather and Hurricane Forecasting Atmospheric process studies
Theme III – Marine and Terrestrial Ecosystems and Natural Resource Management	Ecosystem impacts Transports of dusts/aerosols/nutrients Energy infrastructure
Theme IV – Climate Variability and Change: Seasonal to Centennial	Climate process studies Climate monitoring Numerical model Reanalyses

Table 5. Three Mission Concept Epochs for Winds from Earth Orbit				
Epoch	**1970's – 1994**	**1994 – 2015**	**2016**	**Comments**
Detection Method	Coherent	Coherent & Direct	Coherent & Direct	Coherent & Direct (hybrid) is complementary in covering atmosphere vertically
Backscattering Target	Aerosols only	Aerosols & molecules	Aerosols & molecules	- Uses strength of each detection method to permit much smaller lidars
Pulsed Laser Type	CO_2 gas laser	Solid-state lasers: 2 & 0.355 microns	Solid-state lasers: 2 & 0.355 microns	- Lowers risk (no high voltage, gas recycling, cooled detector on cryocooler)
LOS Wind Profile Shot Accumulation	None, 1 laser shot only	~12 second shot accumulation (120 – 1200 laser shots)	~12 second shot accumulation (120 – 1200 laser shots)	- Lowers pulse energy/pulse rate/optical diameter & representativeness error
Laser Scanner	Continuous conical with single rotating telescope	Step-stare conical with multiple fixed telescopes	Step-stare conical with multiple fixed telescopes	- Step-stare better for shot accumulation - Eliminates large rotating mass & momentum compensation
2-Micron Pulse Energy	20 J	0.25 J	0.04 J	Mission concept changes permitted dramatic drop to 0.25J; change to 200 Hz permits drop to 0.04 J
2-Micron Laser Pulse Rate	10 Hz	10 Hz	200 Hz	Higher coherent pulse rate improves cloud penetration, representativeness error, optical damage probability
2-Micron Receiver Mirror Diameter	1.5 m	0.5 m	0.7 m	Mission concept changed permitted dramatic drop to 0.5 m; recent studies indicate 0.7 m will fit on ISS JEM EF

Table 6. Acronyms	
ASCAT	Advanced SCATterometer
CYGNSS	Cyclone Global Navigation Satellite System
DAWN	Doppler Aerosol WiNd lidar
DWL	Doppler Wind Lidar
ADM	Atmospheric Dynamics Mission
AMV	Atmospheric Motion Vectors
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CYGNSS	Cyclone Global Navigation Satellite System
DAWN	Doppler Aerosol WiNd lidar
DWL	Doppler Wind Lidar
ESA	European Space Agency
GTWS	Global Tropospheric Wind Sounder
GWOS	Global Wind Observing Sounder
ISRO	Indian Space Research Organization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JEM EF	Japanese Experiment Module, Exposed Facility
LaRC	Langley Research Center (NASA)
LAWS	Laser Atmospheric Wind Sounder
LOS	Line of Sight
MOES	Ministry of Earth Science (India)
NICT	National Institute of Information and Communications Technology (Japan)
NIES	National Institute for Environmental Studies (Japan)
NWOS	NPOESS Wind Observing Sounder
NWP	Numerical Weather Prediction
OAWL	Optical Autocovariance Wind Lidar
OSCAR	Observing Systems Capabilities Analysis and Review
OSE	Observing System Experiments
OSSE	Observing Systems Simulation Experiments
PBL	Planetary Boundary Layer
TWiLiTE	Tropospheric Wind Lidar Technology Experiment
WGSBLW	Working Group on Space-Based Lidar Winds
WISSCR	Winds from the International Space Station for Climate Research mission
WMO	World Meteorological Organization

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