Decadal Survey Response due 11/2/15

For

NRC Space Studies Board "Initial Request for White Papers"

Regarding the

"2017-2027 NRC Decadal Survey in Earth Science and Applications from Space"

Reducing NASA's Cost And Risk For An Earth-Orbiting Hybrid Doppler Wind Lidar System That Will Provide Vertical Profiles of Horizontal Vector Wind

Dr. Michael J. Kavaya (NASA Langley Research Center), Dr. Upendra N. Singh (NASA Langley Research Center), Dr. G. David Emmitt (Simpson Weather Associates), and Prof. T. N. Krishnamurti (Florida State University)

The Science

The World Meteorological Organization (WMO) has long desired global measurement of horizontal winds, listing specific measurement requirements for the lower and upper troposphere and stratosphere for the application areas of numerical weather prediction (NWP), aeronautical meteorology, climate, and others [WMO (2012), WMO (2015)]. In a recent paper, the WMO lists "wind speed and direction" in a list of essential variables to improve understanding of climate research [Bojinski et al (2014)]. In the US, NASA, NOAA, DOD, and other agencies place high priority on improving weather forecasts including predictions of severe weather; and they agree that global wind measurements would provide a transformational improvement. Many studies, including Observing System Simulation Studies (OSSEs) have shown the significant impact on NWP and severe weather such as hurricanes that would be made by global winds [e.g., Masutani et al (2010), Ma et al (2015), Atlas et al (2015)]. The space agencies of the US, Europe, Japan, India, and other countries have all expressed a need for wind measurements. The 2007 NRC "Earth Science Decadal Survey" recognized this need and advocated a "3-D Winds" mission [NRC (2007)].

The Space Mission and Preferred Technology Solution

Studies and simulations of global wind missions began in 1978 and have continued to this day. NASA and NOAA scientists have concluded that the best technology to perform this mission with the lowest cost and risk is a pulsed hybrid Doppler wind lidar system [Baker et al (1995), Valinia et al (2006), Baker et al (2014)]. The pulsed hybrid Doppler lidar concept was proposed in 2001 [Emmitt (2001)]. A hybrid Doppler wind lidar system is comprised of two lidars receiving signal from aerosols and molecules, both moving with the wind, for vertical coverage of the atmosphere. Most of the NASA-NOAA studies used coherent-detection lidar at 2-micron wavelength for aerosols, and direct-detection lidar at 0.355-microns wavelength (UV) for molecules.

Relative to direct lidar, the coherent or heterodyne lidar provides very accurate measurements with fewer received photons and a smaller optical receiver diameter, and hence lower laser input electrical power and heat removal [Wu et al (2013)]. The efficiency and accuracy is a consequence of being only required to estimate frequencies with digitized data in a computer. Physics Nobel laureate Charles Townes has stated “It is perhaps not obvious that heterodyne detection can in principle achieve precision in determining a wave’s properties that is limited only by the basic uncertainty principle of quantum mechanics. However, this is the case,” [Johnson and Townes (2000)]. However, the atmosphere has greatly varying concentrations of aerosols, generally decreasing with increasing altitude. As the aerosol concentration falls below a threshold, the probability of a usable measurement decreases.

Relative to coherent lidar, the direct lidar requires more received photons and hence greater optical receiver diameter, and greater laser input power and heat removal; and makes a less accurate measurement since the Brownian motion of the air molecules has much higher velocities than the aerosol Brownian motion. However, the air molecules are found at all altitudes under all weather conditions, allowing the direct lidar to continue to make measurements where the coherent wind lidar does not. Since the molecular backscattered light intensity scales as the inverse of the wavelength to the fourth power (Rayleigh scattering), the short UV wavelength is required for adequate signal.

Space mission studies at NASA have shown that trying to cover the atmosphere vertically with either coherent or direct lidar alone entails greater development risk and spacecraft resources than a hybrid lidar.

Considerable progress has been made in the US over the last decade with both coherent and direct wind lidar technology for space. Coherent lidar at 2 microns is being developed at NASA Langley Research Center for aerosols. Direct lidar is being developed at NASA Goddard Space Flight Center at 0.355 microns for molecules, and at Ball Aerospace & Technologies Corp. at 0.532 microns for aerosols. All three lidars have advanced to aircraft flights. ESA has invested even more than the US in advancing direct lidar. Therefore, the “3-D Winds” mission no longer belongs in Tier 3.

The Pulsed UV Laser in Space Challenge

ESA is developing the first earth-orbiting Doppler wind lidar system called the Atmospheric Dynamics Mission (ADM), a direct detection lidar at 0.355 microns with a 1.5-m-diameter receiver mirror. Due to the mirror size, ADM will aim its laser in only one direction and provide only line-of-sight (LOS) winds. This will be exciting data but will not provide the desired vector horizontal winds. ESA has struggled with the energetic UV photons damaging optical components due to contamination, and ADM had its launch delayed so far from 2007 to 2016. The recent US space mission CATS suffered very fast failure of the UV light output [(McGill et al (2014)], and the UV light is probably the cause of laser degradation of the US LITE space mission [Stadler (1996)]. The contamination comes from outgassing due to vacuum, and floating material due to weightlessness. ESA has spent a lot of money and over 10 years working on this UV problem.

The Way Forward From Here

When a wind-profiling lidar is performing from satellite altitudes, the payoffs for weather and climate forecasts, and for understanding will provide a new dimension. We will have a detailed description of four-dimensional winds around rain-producing intense systems. Data assimilation, the most important component of modeling, will have an unprecedented coverage of winds leading to improvements for weather and climate forecasts. This is what is needed for addressing the extreme rains, winds, and floods.

We recommend the “3-D Winds” mission should move up from Tier 3. The 3 US groups should be funded to continue demonstration of reliable aircraft operation including agreement with other wind sensors, to show space qualification of the technology, and to communicate the path for the technology to space.

An option that will reduce NASA’s cost and risk in implementing the “3-D Winds” mission is to partner with ESA. NASA could provide the coherent wind lidar for aerosols, and ESA could provide the direct wind lidar for molecules using all the lessons learned and capability developed for ADM. In addition, both JAXA and ISRO have indicated a willingness to partner with NASA in providing the 2-micron coherent lidar; which will further reduce NASA’s cost.

References

R. Atlas et al, “Observing System Simulation Experiments (OSSEs) to Evaluate the Potential Impact of an Optical Autocovariance Wind Lidar (OAWL) on Numerical Weather Prediction,” J. Atmos. & Oceanic Tech. 32(9), 1593-1613 (2015)

W. A. Baker et al, "Lidar-Measured Winds from Space: A Key Component for Weather and Climate Prediction," Bull. American Meteorological Society 76(6), 869-888 (1995)

W. E. Baker et al, “Lidar-Measured Wind Profiles – The Missing Link in the Global Observing System,” Bulletin American Meteorological Society. 95 (4), 515-519 (2014)

S. Bojinski et al, “The Concept of Essential Climate Variables In Support Of Climate Research, Applications, and Policy,” Bull. Amer. Meteorol. Soc. 95(9), 1431-1443 (2014)

G. D. Emmitt, “Feasibility and science merits of a hybrid technology DWL,” Proceedings 11th Coherent Laser Radar Conference, 19-22, Great Malvern, UK (1-6 July 2001)

M. A. Johnson and C. H. Townes, “Quantum effects and optimization of heterodyne detection,” Opt. Commun. 179, 183 – 187 (2000).

Z. Ma et al, "Impact of Different Satellite Wind Lidar Telescope Configurations on NCEP GFS Forecast Skill in Observing System Simulation Experiments," J. Atmos. & Oceanic Tech. 32, 478-495 (2015)

M. Masutani et al, "Observing system simulation experiments at the National Centers for Environmental Prediction," J. Geophysical Res. 115 (D7), D07101 (2010)

M. G. McGill et al, "The Cloud-Aerosol Transport System (CATS): A New Earth Science Capability for ISS," Working Group on Space-Based Lidar Winds (May 2014)

National Research Council (NRC), "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," The National Academies Press, Wash DC 2005, (Jan. 2007)

J. H. Stadler, "LITE Laser Transmitter Module Anomaly Investigation Final Report," NASA TR-04-2-08-02 Revision 1 (1996)

A. Valinia et al, "Lidar Technologies Working Group Report," Final Report of the NASA Earth Science Technology Office (ESTO) Laser/Lidar Technology Requirements Working Group (June 2006)

WMO, "Requirements for Observational Data: The Rolling Review of Requirements," (11 Sept. 2012)

WMO, "Observing Systems Capability Analysis and Review Tool", http://www.wmo-sat.info/oscar/requirements (accessed 27 Oct. 2015).

D. Wu et al, "Simulation of coherent Doppler wind lidar measurement from space based on CALIPSO lidar global aerosol observations," Journal of Quantitative Spectroscopy & Radiative Transfer 122, 79-86 (2013)