OAWL: A HIGH-HERITAGE US DOPPLER WIND LIDAR FOR NEXT-GENERATION SPACE-BASED WIND AND AEROSOL OBSERVATIONS

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ABSTRACT

Improving weather forecast skill with global wind profile measurements is part of a larger solution to coping with earth challenges presented by hurricanes, floods, and other natural disasters. ESA's Aeolus Doppler Wind Lidar (DWL) launched on 23 August 2018, demonstrating the first global, vertically resolved, direct wind profile measurements from space. As single line-of-sight (LOS) Aeolus wind measurements demonstrate impact on numerical weather prediction (NWP), its three-year mission lifetime and the absence of a planned follow-on mission will present a challenging data gap for global wind science and NWP centers benefitting from the data. In the U.S., development of DWL missions has been a lower priority, however 2018 saw the NAS 2017 Decadal Survey for Earth Science and Applications from Space and the NOAA Satellite Observing System Architecture (NSOSA) Study highlight the importance of wind measurements from Space-Based DWL. Meanwhile, Ball Aerospace has developed the Optical Autocovariance Wind Lidar (OAWL) instrument to remotely measure wind profiles from space. With support from NASA's Earth Science Technology Office, Ball has demonstrated and validated prototypes of the OAWL instrument in aircraft-based testing. The OAWL approach for space builds on heritage from the aircraft demonstrator, the successful lidar on the CALIPSO mission, and many technologies currently being demonstrated on Aeolus. The OAWL system was proposed to NASA's 2016 Earth Venture Instrument opportunity and, though not selected, was rated selectable in 2018 by NASA's TMCO review panel, indicating system readiness for a space-based mission. The OAWL mission concept builds on Aeolus by providing two LOSs to constrain wind speed and direction, while also reducing stability requirements on laser frequency and platform pointing. The validated OAWL measurement approach builds on the Aeolus legacy, ensuring next-generation space-based wind lidar can provide critical weather information to protect lives and property.

PROVIDING WINDS IN DATA-SPARSE AREAS

Many of the greatest challenges that we as humans face on Earth are related to weather. In many cases, we cannot ignore or fight weather, but with the right warning we can get out of the way of dangerous conditions including hurricanes, tornados, floods, blizzards, and other natural disasters. To use the National Oceanic and Atmospheric Administration's terminology, having the right forecast helps to be "Weather Ready." Providing global citizens with accurate forecasts to protect life and property drives many in the Numerical Weather Prediction (NWP) community to continuously improve forecast accuracy – with consistent progress over the last two decades.[1] Such improvements in NWP forecast accuracy and range stem from several major areas: improved model physics, improved resolution (requiring increased computational efficiency), and increased and improved Earth observations for model initialization and validation. The observations that currently have the greatest per-observation impact on forecast skill tend to be radiosondes, launched from the surface using weather balloons to measure altitude-resolved wind speed, wind direction, temperature, and humidity profiles. Space-based sounding instruments (e.g. ATMS on NPP and JPSS) can retrieve global temperature and humidity information, and scatterometers and provide wind information at the ocean surface, however the greatest unmet need for observations is still direct wind profile measurements through the full troposphere and lower stratosphere, especially over the oceans and lower hemisphere where radiosonde launches are sparse (see Exhibit 1) and thus the model initialization of vertical wind profiles is highly uncertain, leading to uncertain forecasts.

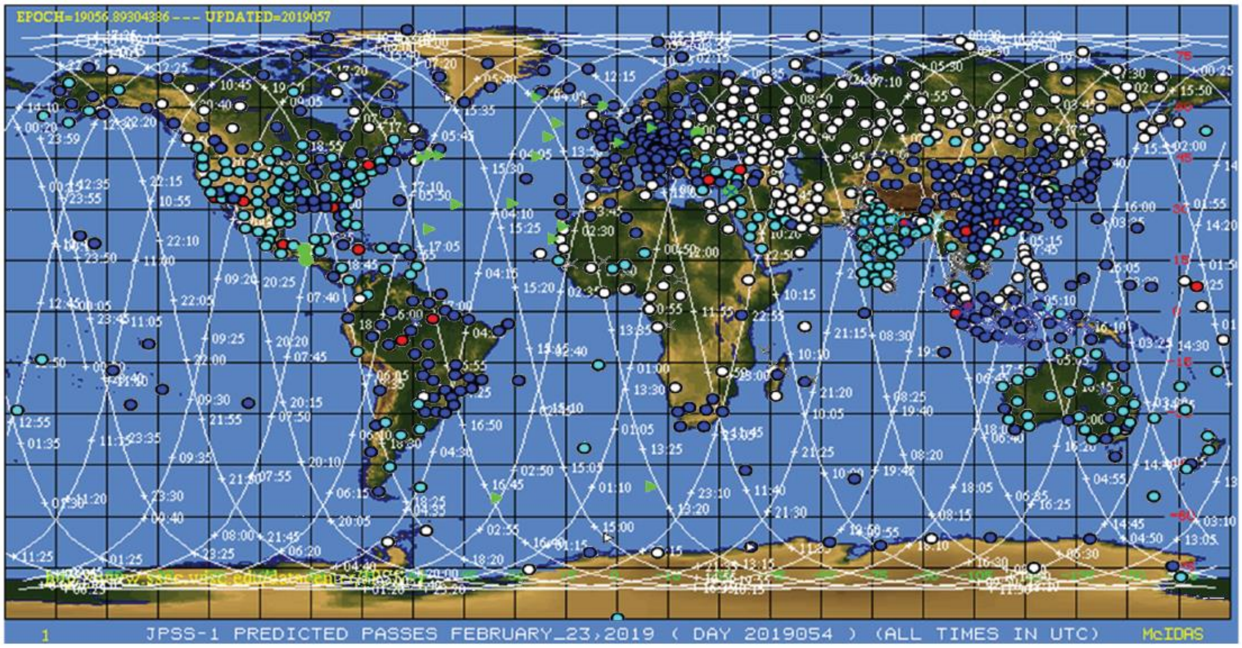

Exhibit 1: Global Radiosonde locations overlaid on 24 hours of coverage from the JPSS orbit (JPSS orbit image credit Space Science and Engineering Center, University of Wisconsin-Madison).

According to the World Meteorological Organization, direct measurements of vertically-resolved wind profiles is still the most significant unmet need in NWP. To address this need, lidar scientists around the world have been developing Doppler wind lidar (DWL) systems for ground, aircraft, and space-based operation. Wind lidars can make direct measurements of winds at regular altitude intervals in the atmosphere, providing wind observations in areas too clear for radar measurements and with much greater vertical resolution and precision than atmospheric-motion-vector (AMV) wind retrieval estimates. Operating a wind lidar from space in a low-earth orbit enables wind profile observations in areas that are otherwise data sparse, helping reduce forecast uncertainty.

In August 2018, the European Space Agency launched the Aeolus mission, containing the ALADIN instrument.[2] Since September 2018, Aeolus has been demonstrating the first global, vertically resolved, direct Doppler wind profile measurements from space. Preliminary studies at the European Center for Medium-range Weather Forecasting (ECMWF) are showing positive impact of Aeolus measurements on the NWP forecast models. The single line-of-sight (LOS) Aeolus mission is limited, however, to a lifetime of three years. There is currently no planned follow-on (from any nation), a situation that will result in a challenging data gap for global wind science and NWP centers that are starting to benefit from the data.

U.S. developments and planning for a future Doppler Wind Lidar mission have not been as high a priority as at ESA, with NASA typically citing lack of technology readiness and/or low science priority for such a mission. In 2018, however, the National Academy of Science 2017 Decadal Survey for Earth Science and Applications from Space (ESAS) listed Atmospheric Winds as one of the observables eligible for a competed “Explorer” mission, and listed DWL among the technologies that could address the relevant science questions.

The NOAA Satellite Observing System Architecture (NSOSA) Study, informed by results from the Space-Platform Requirements Working Group (SPRWG) highlighted the importance of 3D-wind observations, specifically recommending consideration of (among other needs), “*A global three-dimensional winds capability either from a wind lidar (which scored very well in the study) or winds from a cluster of high resolution sounding small satellites*.”[3] With enough sounding satellites one can perform atmospheric motion vector (AMV) retrievals, this approach has not been demonstrated on orbit, nor are AMV’s capable of providing the level of wind accuracy (due to height assignment errors) and precision that can be provided by a wind lidar and that has been demonstrated by ESA's Aeolus.

The potential value of space-based wind lidar observations has been characterized in several observing system simulation studies (OSSE's)[4,5,6] and was the basis of several mission concepts proposed to NASA, dating back to the late 1980s. The technology developments required to perform on these missions, however, was cost prohibitive until ESA took steps to develop the Aeolus mission.

Meanwhile, over the last decade, Ball Aerospace has developed an instrument called the Optical Autocovariance Wind Lidar (OAWL), which uses a relatively-new Quadrature Mach Zehnder Interferometer (QMZI) approach to making DWL measurements.[7,8,9] The OAWL lidar system design builds on the lidar built for the successful CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) mission, which is over 12 years on orbit, including telescopes, background light filters, and data systems. The OAWL approach also incorporates similar technologies currently being demonstrated on Aeolus including seeded lasers and the ability to operate at the 355 nm laser wavelength (though OAWL can also operate at the 532 nm wavelength). With support from NASA's Earth Science Technology Office and Internal Research and Development (IRAD) investments, Ball built, demonstrated, and validated a prototype of the instrument in aircraft-based testing that showed excellent comparisons to wind measurements from radiosondes dropped from the aircraft[10,11] The team has also designed multiple versions of the system for space. In 2016, a mission concept called Aerosol Transport, Hurricanes, Extra-tropical Numerical WeAther using OAWL (ATHENA-OAWL) was proposed to NASA's Earth Venture Instrument (EVI-4) opportunity.[12] The mission proposed putting a build-to-cost, dual-line-of-sight (LOS), 532 nm wavelength version of the OAWL system on the International Space Station. In the 2018 EVI-4 award announcement, the concept was rated selectable by NASA's Technical, Management, Cost and Other (TMCO) review panel, indicating the system's readiness for a space-based mission. The overall proposal received a Category 2 rating, indicating the mission was feasible, but the science (e.g. studies of aerosol transport and tropical cyclones) was a lower priority objective for NASA. With the outcome of the Decadal Survey, the stated NSOSA objectives, and the success of the Aeolus mission, such priorities will hopefully shift again toward supporting a US DWL mission.

OAWL AS A FOLLOW-ON TO AEOLUS

In support of the Aeolus mission, Scientists at ESA and Deutsches Zentrum für Luft- und Raumfahrt (DLR) in Germany, together with partners in European industry, carried out years of technical research and development to understand, model, prototype, test, and validate the ALADIN instrument performance. The teams continue the work to understand and characterize the on-orbit performance, much like the work done for the CALIPSO lidar, but with the added complexity of seeded ultra-violet lasers and measuring Doppler shifted returns. Likewise, similar preparation work continues at Ball to verify and validate the OAWL capabilities and demonstrate how a future mission using the OAWL measurement approach can build on the Aeolus mission, offering additional wind information and reduced risk in some areas.

There are several benefits to the OAWL approach, summarized in Table 1, that allow it to build on the Aeolus mission while reducing some of mission requirements (thus reducing cost). The major advantages are:

- **Second line-of-sight** (LOS): One of the main objectives for building on the Aeolus mission is to provide a second LOS to better constrain measurements of wind speed and direction. While the Aeolus single LOS has been demonstrated to provide up to ~65% percent of the forecast improvement that would be provided by the full vector wind[13], by improving receiver throughput efficiency, a satellite with two LOSs can provide significantly more impact. The all-reflective OAWL QMZI has much greater throughput efficiency than the Fabry Perot (Double Edge molecular channel) and Fizeau (fringe imaging aerosol channel) etalons on Aeolus, improving throughput efficiency.

- **Field widened interferometer**: The field-widened cat-eye interferometer on OAWL (10+ mrad, based on system design) relaxes requirements on laser divergence, telescope wavefront quality, and enables the use of fiber coupling – simplifying overall system alignment and eliminating bias concerns.
- **FPGA-based accumulation**: The OAWL system performs real-time processing in a field-programmable gate array (FPGA), adjusting the reference phase based on the time-zero signal phase for each pulse prior to accumulation. This approach helps relax laser frequency jitter requirements, providing cost savings.
- **Fringe Wrapping**: The QMZI on OAWL measures a full fringe, which wraps without loss, so no signal is lost if the laser frequency shifts or if platform pointing changes over time. This eliminates interferometer-to-laser locking requirements, such as laser frequency stabilization and etalon stabilization.

Parameter	OAWL System Value	Mission Benefit
Number of lines of sight	2 looks, off nadir, forward and aft ±45° azimuth from cross-track	Constrains the full horizontal wind vector profiles
Wavelength	Flexible: 355 nm or 532 nm	355 nm for greater coverage and 532 nm for higher technical readiness, both if desired.
Aerosol & Molecular channels	Short (< 4cm) OPD: molecular& aerosol Long OPD (>50 cm): high precision aerosol Nested OPD design for aerosol & molecular	Flexible QMZI design can be optimized based on mission requirements and budget.
Apriori atmospheric knowledge	No requirement	No altitude-dependent calibrations based on atmospheric return line-width or lineshape are required for OAWL
Interferometer Efficiency	> 90% (based on reflective coatings)	Captures more signal photons for higher SNR
Detection approach	4x PMTs or APDs (wavelength dependent) Every pulse sampled and stored.	FPGA based processing using tie-zero reference phase allows pulse frequency or interferometer phase to shift around on pulse-by pulse basis.
Interferometer FOV Telescope FOV	10+ mrad based on OPD 150-250 μrad	Field-widened interferometer allows for wide field of view (background light limited) → relaxing the telescope alignment requirement.
Laser pulse to pulse Frequency Stability	No requirement: reference phase subtracted pulse by pulse	Cost savings for laser
Fringe Measurement	Full fringe, with 2π wrapping	No loss of signal with laser frequency drifts, platform pointing changes, or interferometer drift.

THE FUTURE OF WIND LIDAR MISSIONS

Aeolus Mission Calibration/Validation

The ESA Aeolus mission launched in August 2018 and the system is operating on orbit, undergoing calibration and validation ("cal/val") studies, with the first on-orbit Cal/Val workshop held in late March 2019. As mentioned above, the Aeolus system operates at the 355 nm wavelength for both the aerosol and molecular channels. Aeolus team members at DLR have an airborne demonstrator for Aeolus, along with a 2-micron coherent detection wind lidar system and performs ongoing comparison studies. The OAWL system, also operating at the 355 nm wavelength, is the only demonstrated 355 nm aerosol wind lidar that can provide a validation measurement from the U.S. side. Funding availability has prevented OAWL from flying with NASA on upcoming airborne cal/val campaigns, however Ball Aerospace is funding ground-based (looking up) studies to provide Aeolus with 355 nm aerosol cal/val measurements over Boulder, Colorado. Current plans also include provide cal/val measurements with the Nested-OAWL molecular channel upon completion later this summer. Both studies provide an opportunity to compare the capabilities of the Aeolus and OAWL systems and to inform next generation missions.

Future Wind Lidar Missions - Full Atmospheric Observations

While studies of the planetary boundary layer are interesting for scientific studies of climate and small-scale dynamics, global NWP impact and forecast improvement requires full atmospheric wind profiles (through the upper troposphere and lower stratosphere) to understand the steering winds and transport that impact the larger scale weather patterns. Measurements of atmospheric dynamics are needed even in areas where aerosols and water vapor content may be very low. Thus, we cannot depend on a single approach to make these types of measurements, especially if we want to have the greatest coverage and thus impact. The community is fortunate that the Aeolus mission is demonstrating the impact of wind observations in various parts of the atmosphere, even with just a single line of sight. Building on the Aeolus studies, future Doppler wind lidar missions can be better shaped to have the greatest impact on forecast.

To that end, while Ball IRAD developments for OAWL focused on reducing system size, weight, and power, the largest focus is on developing and testing a molecular channel to measure winds in regions where no aerosols are present and combining this with the already demonstrated aerosol winds channel. The molecular channel is achieved using the 355 nm wavelength in an interferometer with a short optical-path-difference (OPD) nested inside an interferometer with a longer OPD operating at the 532 nm wavelength (See Exhibit 2).

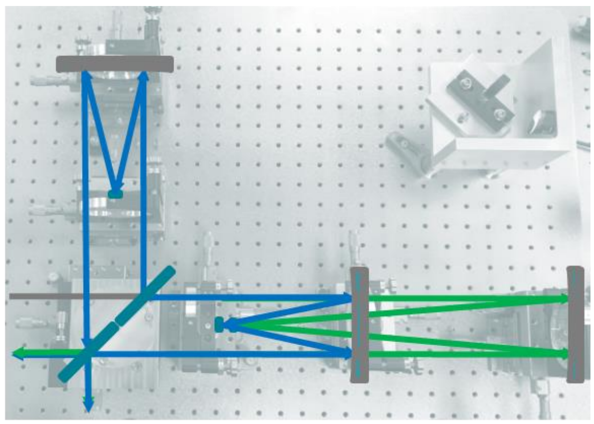

Exhibit 2: Image of the Nested OAWL IRAD testbench interferometer, overlaid with approximate beam paths for the 355 nm (blue lines) and 532 nm (green lines) wavelengths.

The resulting Nested-OAWL interferometer is therefore capable of measuring wind-induced Doppler shifts from both the narrow-bandwidth aerosol returns (using the 532 nm channel) and from the wider bandwidth molecular returns (using the 355 nm channel). The IRAD effort is currently adding hardware to enable testing of the interferometer assembly with atmospheric returns using the original OAWL transmitter and receiver assembly. Both the existing OAWL systems and the new Nested-OAWL system will be used to provide ground-based calibration and validation for the Aeolus mission.

Integrated Wind Observations

While radiosonde and in-situ aircraft observations typically provide the largest per-observation impact on forecast accuracy, space-based observations can have greater overall impact due to the large number of observations. Current approaches to making wind observations from space include surface-based scatterometry (e.g. the Advanced Scatterometer (ASCAT) instrument on board the EUMETSAT Metop satellites), and atmospheric motion vector (AMV) algorithms that rely on multiple overlapping snapshots of visible or infra-red images and/or soundings. These systems look for changes in cloud position (e.g. cloud drift) in imagery from geostationary satellites (such as GOES, Himawari8, and MeteoSat) or in water-vapor gradients from sounders to estimate the speed and direction of winds that may be transporting these atmospheric features. More recently, several organizations have proposed a fleet of small spacecraft (e.g. sets of 3 spacecraft in four different orbits) to create a data cube (2D + time) of water vapor soundings on which to track motion.

While the current AMV approaches have provided significant amounts of wind information, these are retrievals and not direct measurements of wind, so there is still opportunity for improvement. Challenges with passive approaches occur when there are areas of convergence or divergence (e.g. especially over the tropics or with mountain-wave clouds), or where cloud height assignments are highly uncertain, leading to uncertainties in the motion vector wind estimate.[14] By combining these passive approaches with a backscatter lidar, however, the height assignments of the atmospheric layers can be significantly constrained, as demonstrated by Folger & Weissman using CALIPSO lidar data.[15,16]

Based on these results, if a lidar provided not only a corrected height assignment based on backscatter, but also provided an estimate of the wind speed at the cloud/aerosol/feature height, this would further constrain the wind retrieval for the areas where the AMV and lidar were coincident, as indicated in Exhibit 3. By combining these measurements, it becomes possible to anchor the passive wind retrievals with the accurate wind lidar observations and extend the benefit of the lidar measurements using the AMVs in the horizontal surrounding area of the lidar measurement curtain.

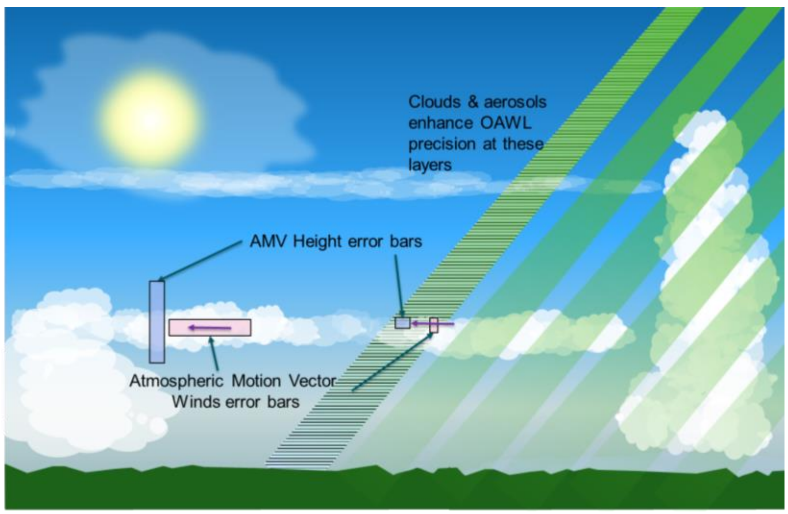

Exhibit 3: Combining space-based Doppler lidar with other motion-vector approaches (e.g. from persistent imaging or multiple sounding satellites) helps to improve the accuracy of the AMV retrievals and expand the impact coverage of the lidar returns

In addition to adding value to passive motion vector wind retrievals, a Doppler wind lidar with a molecular channel (such as Aeolus or Nested OAWL) can also provide wind speed estimates in regions of the atmosphere where only molecules are present and there are inadequate cloud, aerosol, or water vapor features for tracking. A future space-based weather observing system architecture that integrates wind measurements from both passive and active optical systems (as well as infra-red and microwave systems) will provide the best coverage of the full atmosphere. Funding to reduce cost of these systems to enable more frequent launches, increased temporal coverage, and injection of new technologies should be a high priority for our nation.

CONCLUSIONS

ESA's Aeolus Doppler wind lidar is currently on-orbit, demonstrating full-tropospheric, global wind profile measurements. Studies are currently in progress to demonstrate the impact of the wind lidar measurements on improving weather forecast skill. In preparation for the next generation wind lidar observations, Ball Aerospace has developed, airborne tested, and validated the Optical Autocovariance Wind Lidar (OAWL) system. OAWL system designs proposed for space-based operation have been reviewed and rated selectable by NASA TMCO. The OAWL approach also offers configurations for measuring winds over the full troposphere (both aerosol laden and clean regions) which is critical for longer term forecasts. By combining an OAWL Doppler wind lidar system that directly measures winds with passive imaging and sounding system wind retrievals, the future weather architecture can benefit from increased wind accuracy (from the lidar) and greater horizontal coverage (from sounders). The OAWL measurement approach, ready to build for an operational demonstration, builds on the Aeolus mission by adding a second look while reducing technical requirements to reduce overall cost. Injecting global wind lidar measurements from systems such as Aeolus and OAWL will provide better model initialization, thus reducing forecast error.

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