First Demonstration of an Optical Autocovariance Direct Detection Wind Lidar

Christian J. Grund, Sara Tucker, and Tom Delker
Ball Aerospace & Technologies Corp.
1600 Commerce St.
Boulder, CO 80301
cgrund@ball.com

***Abstract*— The Decadal Survey 3-D winds mission is intended to help fill critical currently unmet environmental sensing needs. Last year we reported on the design, development, and validation plans for an Optical Autocovariance Wind Lidar (OAWL). This year we report on first OAWL wind lidar operations and preparations for impending ground and airborne validation campaigns. OAWL uses a unique high resolution interferometric receiver and direct-detection to efficiently and accurately measure the profiles of wind speed by resolving the optical Doppler shift of aerosol backscatter from a pulsed laser at 355nm. Together with an etalon front end measuring the winds from molecular backscatter in clear air, the Integrated Direct Detection (IDD) "hybrid" approach offers a single laser and wavelength architecture for the 3D-Winds mission providing an alternative "hybrid" approach that promises to reduce cost and complexity while achieving the required full atmosphere profiling capability (i.e. aerosol + molecular backscatter winds). A three year IIP is in progress that has completed an operational OAWL lidar system. We show first ground wind profile data from this system and discuss plans for full ground and airborne validations this year.**

Keywords-component; Lidar; Doppler wind lidar; Optical autocovariance; 3D winds mission

I. Introduction

Winds are key dynamic drivers of the atmospheric mass and energy fields. Insufficiencies and inaccuracies in current wind observations, particularly over the oceans, in the southern hemisphere, and in the tropics, lead to uncertainty in the modeling of global atmospheric circulations, limiting weather forecasting accuracy and diminishing our understanding of water, chemical species, and energy transport. The NASA Decadal Survey specifically states that: Tropospheric winds are the number one unmet measurement objective for improving weather forecasts. The Survey defines a 3-D Winds mission that identifies Doppler Wind Lidar (DWL) in low earth orbit (LEO) as the key technology needed to meet the global wind profiling objectives [1]. To profile winds, DWL's measure the line of sight optical Doppler frequency shift from aerosols and molecules as a function of range. Backscatter from molecules is ever-present but spectrally broadened by thermal motions diminishing the achievable wind measurement precision. Aerosols produce insignificant backscatter spectral broadening providing the best wind information, but are not always present. A hybrid lidar [2] measuring winds from both aerosol and molecular backscatter therefore maximizes the availability of wind profiles. The Optical Autocovariance Wind Lidar (OAWL) [3] is a direct detection DWL approach that uses a unique high resolution (10^9-10^{10}) interferometer to measure line-of-sight (LOS) aerosol backscatter winds to <0.5 m/s precision. When operated at UV wavelengths (~355nm), OAWL can simultaneously measure molecular and aerosol backscatter winds; however, a more photon-efficient Integrated Direct Detection (IDD) architecture, shown in Figure 1, employs a dual-edge etalon pre-filter to separately measure the Doppler offset of the molecular fraction of the backscatter return, while leaving the aerosol-backscatter-dominated center of the Doppler shifted spectrum for analysis by the high resolution OAWL. The IDD hybrid approach uses a single transmit laser and receiving system with relaxed several-wave telescope optical requirements, making it much simpler, lower mass, lower cost, and more power efficient than the alternative hybrid approach that uses a combination of a 2 micron Coherent Detection DWL [4] for aerosol wind profiling combined with a separate 355nm dual-edge etalon direct detection DWL [5] for measuring the molecular component.

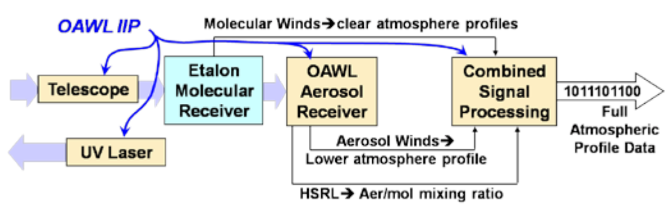

Figure 1 The Integrated Direct Detection (IDD) hybrid architecture that promises to provide full wind profiles using a conventional double-edge etalon to resolve the molecular backscatter component and an OAWL receiver to resolve the aerosol backscatter component (normally rejected by the etalon front end). Only one laser transmitter is required and the required optical wavefront quality is significantly reduced compared to a coherent detection system.

In addition to winds, the OAWL technique can be used to measure calibrated aerosol optical properties at multiple simultaneous wavelengths using the High spectral resolution lidar method (HSRL) [3]. This leaves open the possibility to fly a combined single-instrument wind and HSRL lidar, providing additional potential cost savings and improved science data for Decadal Survey missions.

The primary objectives of the IIP are to raise the OAWL DWL technology from TRL3 to TRL5 by taking the multi-wavelength field-widened OAWL receiver built under Ball internal funds, integrating it into a complete lidar system (telescope, laser, data system, framework) configured to fit in a WB-57 aircraft palate, ground validate the OAWL system against a coherent Doppler lidar, and then validate the system performance from the WB-57 against wind profilers and a ground-based coherent DWL system. We are in the last year of a 3-year IIP, and have demonstrated first aerosol wind measurements for an OAWL system and discuss the first wind measurements and ground and airborne validation plans.

II. The OAWL System

At the last ESTO conference we discussed the theory, architecture, development progress, and demonstration plans for the OAWL DWL system. The integrated system is shown in Figure 2.

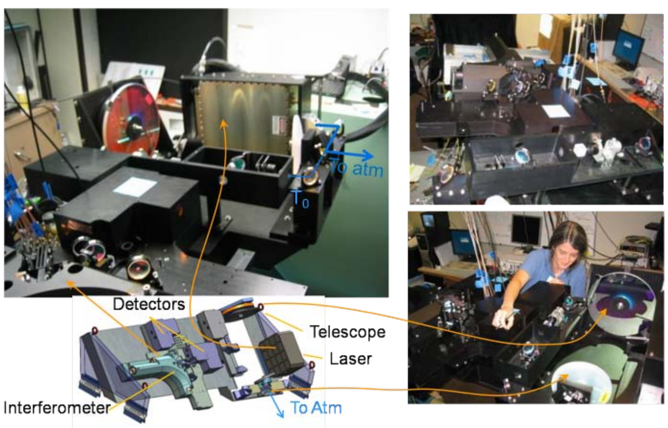

Figure 2 The integrated OAWL IIP system in the lab. The system is designed to fit in a 6' WB-57 pressureized pallet with a fixed 45ºpointing orthogonal to the flight direction.

III. First OAWL Ground Measurements

After final delivery of the laser in November 2010, system integration was rapidly completed, and first engineering tests were performed in late December 2010 and early January 2011 from a small lab on the rooftop of one of the buildings on the Ball Boulder campus. The observation configuration is shown in Figure 3. Due to eye-safety considerations and the proximity of a small airport to the Ball campus, the lidar was confined to fixed pointing operations on a ~3.8º upward slope along a mountain valley to the west of town. The Boulder Atmospheric Observatory (BAO) tower is located ~10 miles ENE of the lidar is flat rural terrain. The BAO tower is 1000' tall and has anemometers at 10, 100m and 300m altitudes AGL.

Figures 4 through 7 show examples of the preliminary wind profile data. During these tests, only the analog channels were fully functional, so the data have limited range. We have since brought the photon counting channels on line but these data had not been fully processed at the time of this writing. The plotted bars and statistical information are explained in the caption to Figure 4.

Figure 3 The experiment domain is shown with bird's-eye views of the lidar location atop a spacecraft assembly building on the Ball campus and the BAO tower ~10 mi to the ENE of the lidar in relatively flat unobstructed terrain. Because of the proximity of the Ball location to a nearby airport, eye-safety restrictions constrain the lidar to point up at a ~3.8º slope along a mountain valley to the west. Not the most ideal conditions for intercomparison. Nonetheless, there is reasonable agreement between the lidar and tower wind profiles.

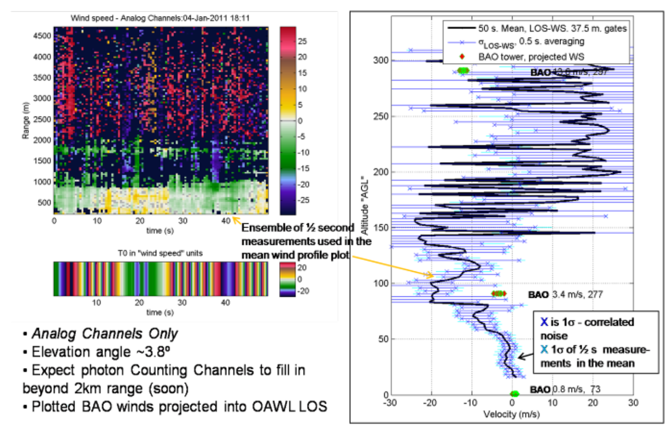

Figure 4 OAWL line of sight (LOS) analog channel wind measurements plotted in m/s (color) against LOS range as individual ½ s averaged profiles (upper left), and as a mean of the 50 s ensemble as a function of AGL altitude (right). The teal bars about the mean indicate 1σ of the 1/2s measurements, while the darker blue bars indicate 1σ of the 1/2s constituents with estimated correlated noise (e.g. due to wind turbulence) removed. Also shown in green are the 10m, 100m, 1nd 300m BAO tower measurements with the true speed and direction indicated. The green markers have been projected into the lidar pinting direction. The width of the green markers indicates 1σ of the anemometer measurements over a 1 minute period.

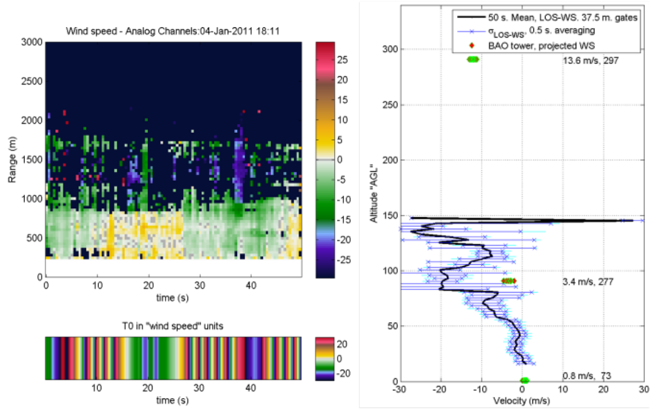

Figure 5 Same as Figure 4, but with the plotted data thresholded on a T_0 contrast >0.4 and an atmospheric return contrast >0.04. +

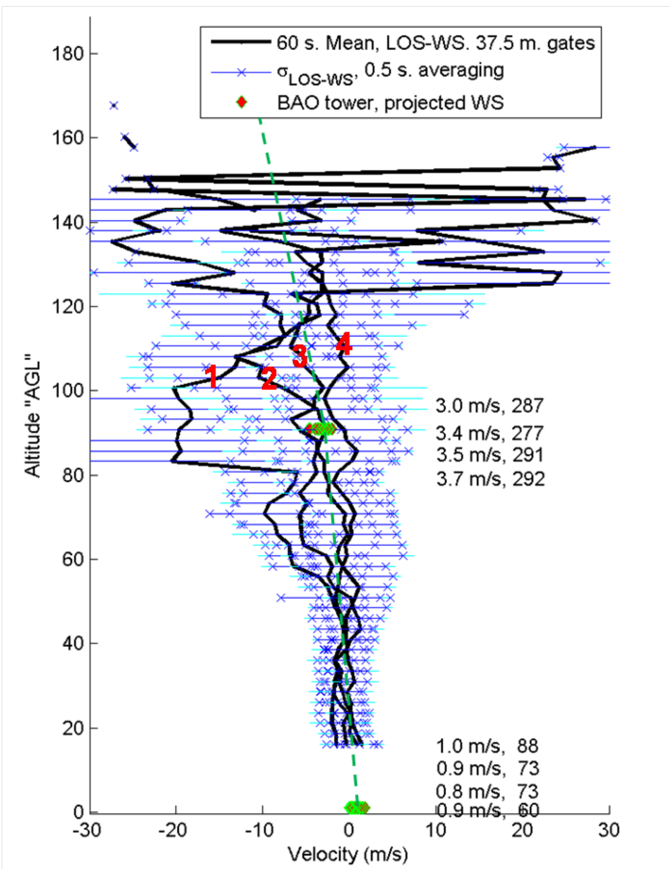

Figure 6 Four sequential profiles (1-4), are plotted together to show a temporal progression and demonstrate the agreement between the tower measurements and the independent profiles.

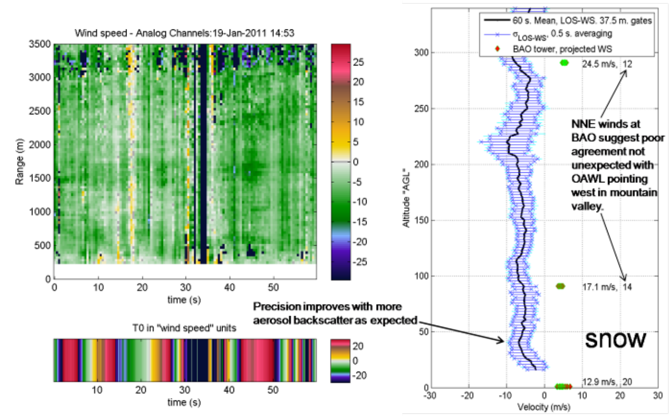

Figure 7 A profile in light snow demonstrateds the improvement in wind estimation with increasing aerosol backscatter, a demonstration that the interferometer is resolving the aerosol backscatter component.

IV. IIP Test Plans

After the shake-out testing is complete the IIP program calls for two rigorous testing and validation periods. The first validations will be provided by ground testing alongside the well characterized NOAA mini-MOPA coherent detection DWL system. These tests will be conducted at the NOAA Table Mountain facility just north of Boulder, CO. The ground testing preparation are complete and the schedule is only pending receipt and integration of the correct laser.

In the Fall of 2011, we plan to execute the high altitude flight tests that will result in raising the OAWL technology to TRL-5. An overview of the flight test plan is given in Fig. 8. The plan includes flights out of Houston to and from Boulder, CO, circling many wind profilers in the NOAA network. The system does not include a scanner, so the flight path will carry the beam path (nominally 45° to vertical) about each profiler simulating a scan and allowing the vector wind profile to be derived. The flight path will cover a variety of terrain and ocean backgrounds, providing observation opportunities under different cloud conditions. Higher temporal and spatial resolution profiles will also be provided by one of the NOAA coherent detection DWL systems in the Boulder area during overflights.

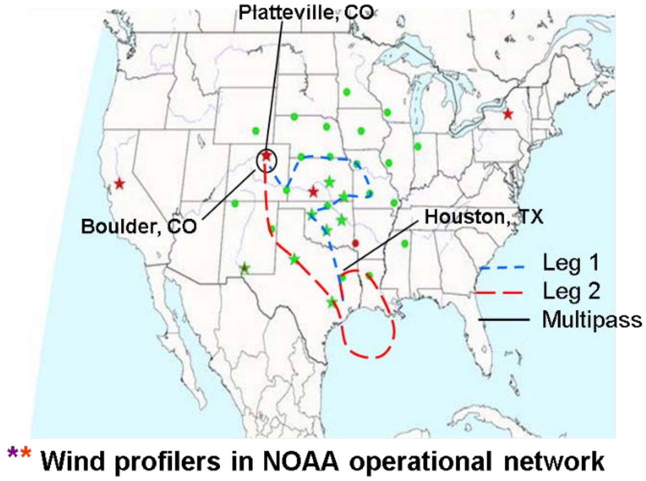

Figure 8 The airborne test plan the OAWL IIP system includes flights out of Houston to and from Boulder, CO, circling many wind profilers in the NOAA network. The flight path will cover a variety of terrain and ocean backgrounds, hopefully providing observations under different cloud conditions. Higher temporal and spatial resolution profiles will also be provided by a coherent detection DWL systems in the Boulder area..

V. Next Steps

For the WB-57 flight tests, the data system has to collect geolocation and attitude information provided by the WB-57 platform via an AIRINC interface, as well as housekeeping and health and status data from the instrument itself including a backup accelerometer to determine the OAWL attitude. For the flight tests, the system must. run in a fully autonomous mode. Significant effort will be dedicated to testing operations over all conceivable flight conditions including brief and extended power outages. Final assembly of the system in the pallet after the ground validations are complete will include air ducting plenums and installation of auxiliary heating and cooling capability. By design, in the event of complete power failure to the pallet, insulation and thermal mass are sufficient to keep the system above survival temperature for at least 1 hour while the plane descends and lands.

VI. Conclusions

The first complete OAWL wind lidar system has been built under this IIP and has demonstrated preliminary wind measurements. The system has been constructed for installation and autonomous operation in a WB-57 aircraft pallet and is suitable for aircraft testing to 50k'. It incorporates many of the system design features required for a space-flight-path sensor that is scalable directly to a sensor meeting the 3D wind mission requirements. Preliminary wind profiles demonstrate that we have some work to do with regard to stabilizing the T0 phase measurement, but are nearing readiness for a ground validation campaign alongside a seasoned NOAA coherent detection Doppler lidar. The WB-57 flight validation schedule has been delayed by aircraft availability and is now expected in late October 2011. A successful test program will result in an available alternative "hybrid" architecture for the 3-D winds mission that promises to save significant cost, mass, and power, while offering the potential to combine 3-D winds and other important environmental missions [12]. Once validated, we plan to fly the current system in support of atmospheric science missions.

Acknowledgements

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