Comparing and contrasting the Optical Autocovariance Wind Lidar (OAWL) and coherent detection lidar

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We describe the basic theory of the direct detection optical autocovariance approach to Doppler wind lidar (DWL) and review the history of Mach Zehnder Interferometry for DWLs including development of the Optical Autocovariance Wind Lidar (OAWL) at Ball Aerospace and Technologies Corp. Results of a validation study for the 355 nm OAWL system, performed via comparison with a 9.35 µm coherent detection system are provided. We close with a discussion on contrasts between coherent detection systems and the OAWL approach in the areas of laser coherence length, detection sampling rates, and wavelengths.

1. Optical Autocovariance

The Optical Autocovariance Wind Lidar (OAWL) instrument is a modified Mach Zehnder interferometer that uses polarization multiplexing and four detectors, each separated by $\lambda/4$ from the next, to measure the fringe contrast and fringe phase in a modified Mach Zehnder Interferometer. The OAWL measurement operation consists of measuring the phase of autocovariance fringe produced by light in the interferometer, referenced to four defined phase points.

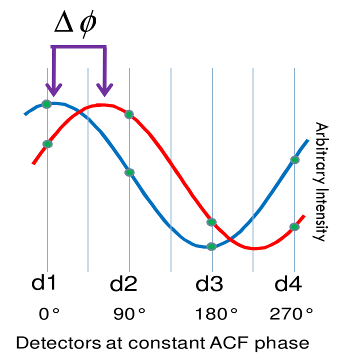


Figure 1. Example fringes in the OAWL Interferometer from the outgoing (blue) and Doppler shifted (red) illumination. The detectors are at a constant Autocovariance (ACF) phase, separated by $\lambda/4$ from each other. As the frequency changes relative to the outgoing pulse frequency, the interferometer fringe moves by a phase offset $\Delta\phi$.. The phase offset is estimated and turned into a wind speed according to Equation (1).

A sample of the outgoing pulse is used to determine the fringe phase of the interferometer at time T0 (the blue line in Figure 1). Given a Doppler shift of the backscattered light, related to the laser wavelength λ, and the line-of-sight (LOS) wind v_{LOS} via

$$\Delta f_D = \frac{2v_{LOS}}{\lambda}, \tag{1}$$

the return light will produce a fringe with a different relative phase (red line in Figure 1). The fringe phase shift ($\Delta\phi$, in fractions of 2π) is related to the Doppler shift Δf by

$$\frac{\Delta\phi}{2\pi} = \frac{\Delta f_D OPD}{c}, \tag{2}$$

where OPD is the optical path difference of the interferometer (~1m for the initial build of OAWL) and c is the speed of light. The precision of the LOS wind speed estimate is proportional to the wavelength of illumination, and inversely proportional to the SNR and the optical path difference (OPD) in the interferometer:

$$\sigma_{v_{LOS}} \propto \frac{\lambda}{SNR \cdot OPD}. \tag{3}$$

The SNR of the return is tied to the lidar equation, detector characteristics, and to the contrast of the fringes which is a function of the relationship between the illumination bandwidth and the free spectral range, FSR, where FSR = c/OPD;

2. Optical Autocovariance and Michelson/Mach Zehnder interferometer wind lidars

The concept of a Mach Zehnder Interferometer (MZI) for Doppler wind lidar measurements is not new to OAWL. In 1995 Schwiesow and Mayor presented at the Coherent Laser Radar Conference (CLRC) on the use of a modified Michelson interferometer to directly measure optical autocovariance (ACV) for wind measurement.[1] They suggested the use of either a three stepped mirror to measure three points on the ACV function, or the use of polarization division, implemented using quarter wave plates to introduce λ/4 steps between detector positions on the ACV function, as was eventually implemented in four channel MZI approaches. The concept was further developed by Liu and Kobayashi (two-channel and four-channel discriminator concepts) for aerosol winds,[2] and later by Bruneau for a molecular wind lidar,[3] then by Bruneau and Pelon (aerosol winds and aerosol properties),[4] and in 2004 Bruneau et al described the first measurements of wind using a 10 cm OPD MZI.[5] Please see the references for additional details on these systems.

To address the need for an aerosol winds measurement from space, Ball Aerospace and Technologies Corp began development in 2004 of Optical Autocovariance systems under internal research and development (IRAD) funds. The first Ball system used the stepped-coating, three-phase approach originally described by Schwiesow.[1] This design was demonstrated by Grund et al. in a laboratory setting in 2006 and validated on the rooftop using a sonic anemometer. In 2007, Grund and Pierce designed an absolute-referenced, field-widened, multi-wavelength, modified-Mach-Zehnder interferometer receiver.[6] (Patents for the method and apparatus: US7929215B1, US8077294B1). Development of this new interferometer continued at Ball through 2008-2009 resulting in a field widened, multi-wavelength (Nd:YAG wavelengths of 355 nm and 532 nm), meter-class OPD interferometer receiver. In 2008, NASA Earth Science Technology Office funded an Instrument Incubator Program (IIP) to turn the Ball-built interferometer into a full Doppler wind lidar through the addition of a laser transmitter, telescope, and data acquisition system.[7] The IIP funding also covered successful ground validation tests, discussed in the next section, and successful NASA WB-57 flight validation tests of autonomous operation of the 355 nm OAWL.[8]

3. Preliminary OAWL performance results

The initial OAWL instrument validation was performed by taking data during a ground-based test with the NOAA Earth Science Technology Laboratory mini-MOPA 9.355 µm coherent detection Doppler wind lidar (MOPA)[9]. The MOPA and OAWL systems were both set up pointing out over Table Mountain Test Facility (north of Boulder, CO) at 17° (NNE) azimuth and 0.3° elevation. The test took place 11-21 July 2011 during which approximately 15 hours of coincident data were acquired. Figure 2 contains images of processed line of sight (LOS) wind estimates for data acquired from each system on 13 July 2011. The top panel contains the 355 nm OAWL data processed with 30 m range gates and 2 seconds of accumulation (1600 samples/estimate). The bottom panel shows the 9.355 µm NOAA mini-MOPA data processed with 150 m range gates and 0.5 seconds of accumulation (1500 samples/estimate).

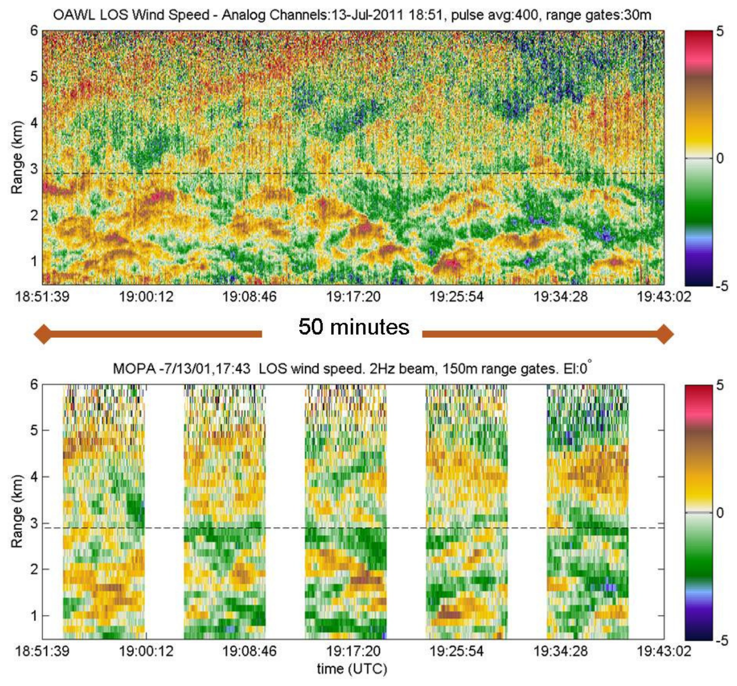
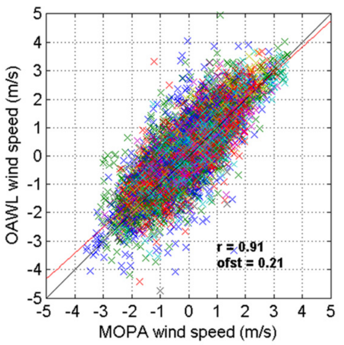
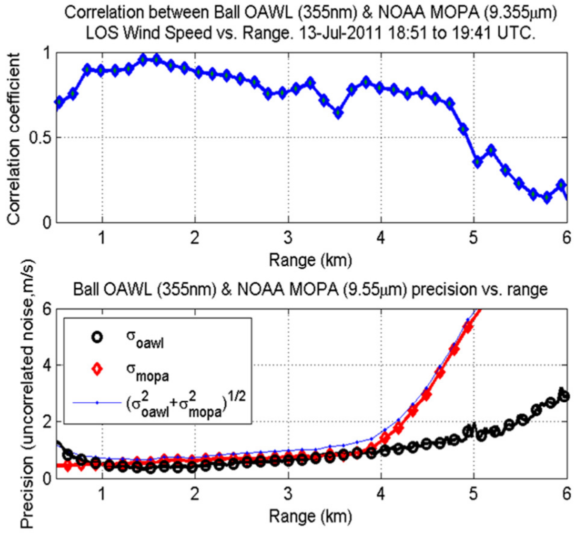


Figure 2. Left: Images of data acquired during the OAWL ground-test validation study. Top panel: OAWL data processed with 30 m range gates and 2 s accumulation. Bottom panel: the NOAA Mini-MOPA data processed with 150 m range gates and 0.5 s accumulation. Below: scatter plot of all OAWL and mini-MOPA LOS velocity values between 1 and 5 km.



The two data sets were then decimated and interpolated (OAWL in range, MOPA in time) to be on the same 2 second and 150 m range grid. Figure 2, Right contains a scatter plot of all (i.e. no thresholding was applied) of the OAWL versus MOPA LOS speed estimates between 1 and 5 km. The comparison resulted in a correlation coefficient of r = 0.91, limited by the precision of both systems. For each 150 meter range gate, the correlation coefficient between the two signals was then calculated and is plotted versus range in the top panel of Figure 3. The bottom panel shows the uncorrelated noise uncertainty (precision) for each system versus range. Note how the coherent system uncertainty increases very quickly after 4 km, but the OAWL uncertainty increases more slowly with range, as is typical for direct-detection systems.


Correlation between Ball OAWL (355nm) & NOAA MOPA (9.355μm) LOS Wind Speed vs. Range. 13-Jul-2011 18:51 to 19:41 UTC.

Ball OAWL (355nm) & NOAA MOPA (9.55μm) precision vs. range

Figure 3. Top panel: Range dependent correlation between the Ball OAWL system data and the NOAA mini-MOPA system data after interpolation of both systems onto the same grid. Bottom panel: Calculated precision of each system versus range.

4. OAWL and coherent detection contrast and comparison

Having demonstrated the performance of the first OAWL system for aerosol wind lidar, we discuss some of the main differences between the OAWL system and coherent detection wind lidar. Differences in scattering strength for various wavelengths, and in sensitivity between direct detection and heterodyne detection systems has been discussed in other reviews and so is not included here.

4.1 Requirement on Coherence Length: L_c

Like a coherent detection system, in order to measure the Doppler shift of light backscattered from aerosols with sub meter per second precision, OAWL requires a laser with a pulse bandwidth that is narrow relative to the free spectral range of the system (OAWL FSR < 200 MHz for an aerosol only configuration). In terms of coherence length, (where bandwidth < c/L_c) this requirement implies that the coherence length of the laser pulse must be greater than the optical path difference of the interferometer (2-3 times, or ~3 is sufficient meters for the aerosol OAWL). If OAWL is configured to also measure the wide bandwidth molecular return, then a shorter OPD may be used (like that used in the system by Bruneau & Pelon[5]), and a laser bandwidth on the order of a few hundred MHz would be adequate, however the overall uncertainty will increase due to the larger free spectral range. These wider bandwidths allow for shorter pulses, and so the range resolution is limited only by sampling rate.

In the case of coherent detection the pulse bandwidth also needs to be narrow (i.e. 5-20 MHz) however the strict coherence length requirement falls onto the local oscillator. The coherence length of the laser must be greater than the round trip length to the farthest range. For most surface based applications, this is 2 to 20 km (i.e. <15 kHz bandwidth). For aircraft such as the Global Hawk, flying at 20 km altitude with the beam pointing at least 40 degree nadir, the coherence length needs to be on the order of 60 km (<5 kHz). For Space-based applications, (i.e. a 400 km orbit, 40 degree nadir pointing angle) the round trip distance, and thus the coherence length requirement is on the order of 12,000 km (e.g. < 25 Hz). Despite the low power requirement (a few mW) on the continuous wave local oscillator, this bandwidth requirement, in a space-based environment, is quite demanding. To achieve the narrow pulse bandwidths, long temporal pulses must be used, thus limiting the range resolution of coherent detection system.

4.2 Sample Rate

For all types of Doppler wind lidar systems, the rate at which the detected signals are sampled is tied to the detection bandwidth and thus sets the levels of bandwidth-related noise. For space-based applications, it also sets the minimum distance from which a ground return may be separated from the atmospheric return above it.

In the case of coherent detection, the sample rate also sets the wind-speed-detection bandwidth (e.g. 100 MHz sample rate results in a 50 Mhz (±25 MHz) bandwidth, which for 2μm system is ±25 ms^{-1}). Any LOS speeds outside the narrow bandwidth are attenuated and thus rejected. To remove any platform induced Doppler shift, a variable electronic local oscillator is required to ensure that platform offsets are removed prior to sampling and that the sample bandwidth is centered around the zero-wind Doppler shift. To measure a larger range of line of sight frequencies, the bandwidth must either be larger (thus increasing the noise level, decreasing the precision), or its center must be continuously adjusted (again using a variable local oscillator) to target only the higher wind speeds.

In the case of OAWL, however, bandwidth is tied only to range resolution. As is the case for all direct detection wind lidars, one can choose to have higher range resolution at the cost of higher noise levels from larger sample bandwidths. Because the autocovariance function is continuous, platform induced Doppler shifts greater than the free spectral range of the system, "wrap around" (i.e. cause a ±2π phase shift) and are not attenuated or rejected. Knowledge of the platform motion is all that is required to unwrap the platform induced phase offsets in software - no variable local oscillator is required. If the wind-based Doppler shifts are higher than the FSR of the system, these may be tracked (by looking for jumps in the phase) and again removed in software.

4.3 Wavelength Requirement

The optimum wavelength for a coherent Doppler lidar (CDL) depends on several factors. For a given wind speed measurement range (e.g. ±25 ms^{-1}), the required sample rate (e.g. 100 MHz) is tied to the wavelength (e.g. 2 micron) of a coherent Doppler Lidar through the relationship in Equation 1. Increasingly shorter wavelengths require increasingly larger sample bandwidths (higher speed analog-to-digital converters, more processing power, and higher noise levels) to achieve the same wind speed measurement range. Shorter wavelengths are also more susceptible to the effects of refractive turbulence, thus reducing precision of the measurement. However shorter wavelengths are able to take advantage of a larger portion of the atmospheric aerosol size distribution, thus enabling them to make measurements in low aerosol environments, and improving their SNR in situations with high aerosol loading.

The OAWL concept, however, can be designed to operate at any wavelength without needing to adjust the sampling rate of the system. The current OAWL system operates at two wavelengths, 355 nm and 532 nm, so that it may also be used to retrieve aerosol optical properties (extinction, backscatter, and depolarization ratio at each wavelength, and color ratios of each). The same type of detectors and sampling hardware are used for both wavelengths. Larger wavelengths (i.e. > 1 micron), however, will increase the uncertainty of the measurement for two reasons: 1) the uncertainty is proportional to the wavelength (for the same OPD) and 2) longer wavelengths have lower backscatter values, thus reducing the SNR of the measurement. Short wavelengths will result in increased molecular backscatter into the receiver which, for a long OPD, adds only shot noise, but for a short OPD results in increased SNR.

5. Conclusions

Through side-by-side ground comparison testing we have demonstrated that the OAWL system, a direct detection Mach Zehnder Interferometer wind lidar operating at 355 nm, can achieve measurement uncertainties in wind speeds from aerosol returns similar to those from coherent detection systems operating in the same environment. In contrast to coherent detection, the OAWL approach allows the use of shorter coherence length (wider bandwidth) lasers, slower sampling rates, and a wider range of usable wavelengths that may be tuned to match atmospheric aerosol conditions throughout the atmosphere. These differences, along with the space heritage for the Nd:YAG lasers being used for OAWL, make the OAWL approach an attractive alternative for a space-based wind lidar mission.

6. Acknowledgements

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7. References

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