A Comparison of Single- and Dual-Doppler Scanning Lidar Wind Vector Retrievals with In-Situ and Vertical Lidar Measurements as they apply to Wind Energy Resource Assessment

K.S. Barr[1], J. Sharp[2], D. Mcreavy[1], D.E. Wolfe[3]
[1]Lockheed Martin Commercial Ventures, [2]Sharply Focused LLC, [3]National Oceanic and Atmospheric Administration

Lockheed Martin Space Systems Company, Commercial Ventures (LM) conducted a study to assess the quality of single- and dual-Doppler wind vector retrieval methods for use in wind energy Wind Resource Assessments. The experiment was conducted at and near the Boulder Atmospheric Observatory (BAO), a 300 meter tall lattice tower owned by the National Oceanic and Atmospheric Administration (NOAA). LM installed standard wind industry Class 1 anemometers and vanes at three levels and on both sides of the tower as "truth" sensors. Additionally, vertical lidar units (VL) were placed near the base of the tower and at two other remote locations. Two WindTracer® Scanning Doppler Lidar units were installed roughly 2km southwest and 2km east of the BAO tower and were configured in both scanning and staring beam modes to take data for comparison with the tower measurements and VL datasets. Nearly three months of data was taken during the first quarter of 2013.

1. Introduction

The latest generation of the WindTracer® Scanning Doppler Lidar has the longest range of any commercially available lidar on the market. In a typical volume scan mode it is able to measure wind fields throughout the boundary layer to ranges commonly in excess of 15 km, every few minutes. With range resolution as low as 100 meters and a scan resolution smaller than 1 degree of azimuth, an incredibly detailed wind field, covering hundreds of square kilometers through thousands of meters of depth can be observed and tracked. The ability to observe the wind field in such great detail has led to the device enjoying widespread acceptance at airports, ensuring that controllers and pilots are aware of dangerous weather hazards and allowing reduced wake separation spacing between aircraft in appropriate conditions. Application to the wind energy industry is an obvious next step.

Wind energy is an industry where differences in average wind speed as small as 0.1 m/s can mean the difference between a viable or non-viable project, and wind farm developers are understandably cautious about embracing new remote sensing technology. Therefore, the objective of the study is to demonstrate the capability of the WindTracer® Scanning Doppler Lidar to measure the wind field while simultaneously verifying that the instrument's accuracy is comparable with measurements taken by tower-mounted anemometers and vertically pointing lidars, both of which are currently accepted measurement methods.

2. Measurement Locations and Equipment Configuration

The experiment was conducted near Erie, Colorado beginning January 9, 2013 and ending on March 25, 2013. Erie is home to the Boulder Atmospheric Observatory (BAO), a 300 meter tall lattice tower that was constructed specifically for remote sensing studies. BAO is located roughly 25 km east of the Rocky Mountains in minimally complex farmland terrain. The overall site layout is shown in Figure 1. The figure shows the location of BAO along with the locations of the two WindTracer units and the three VL units.

2.1. WTX WindTracers

Two WTX WindTracer units were installed at locations suitable for measuring the winds at BAO and above the three VLs. One WindTracer was installed at a business 2.18 km southwest of BAO. This WindTracer is denoted as the Boulder Flatworks WindTracer (BFWT) and is shown in Figure 3. A second WindTracer was installed at a business 2.12 km east of BAO and is denoted as the Split Rail Fence WindTracer (SRFWT) shown in Figure 2. The BFWT and SRFWT locations were chosen for their visibility of the tower, VL sites, and for their relative locations as they pertain to dual-Doppler analysis.

Both WindTracers were configured for two types of data collection for the entirety of the campaign with the intention of providing deeper insight into the performance of the WindTracer units. An actual Wind Resource Assessment would not generally be conducted in this manner, as uninterrupted, continual monitoring of the wind information is desirable.

During the first 50 minutes of each hour the WindTracers were operated in Plan Position Indicator (PPI) scan mode with a set of tilts designed to provide guaranteed single- and dual-Doppler wind vector retrieval capabilities at the BAO site at 60, 90, 100, 120, 150, 200, and 300 meters above ground and above the two remote vertical lidars at 60, 90, and 120 meters above ground. The resulting volume scan patterns required five minutes to complete guaranteeing at least two measurements at each point in every ten minute analysis period throughout the campaign; ten minutes being the standard analysis averaging interval in the wind energy industry.

During the final 10 minutes of each hour both WindTracers were configured in a high data rate (10 Hz) staring beam mode with the beam directed at a point within a few meters of the northwest-side 100 meter anemometer on the BAO tower for detailed dual-Doppler and radial wind comparisons with the 100m anemometer and vane, and the vertical lidar near the tower base.

Figure 1: Experiment layout showing the location of BAO, the two WindTracer units, and the three vertical lidars.

Figure 3: Boulder Flatworks WindTracer (BFWT) located 2,183 meters southwest of BAO.

Figure 2: Split Rail Fence WindTracer (SRFWT) located 2,120 meters east of BAO.

2.2. Boulder Atmospheric Observatory

The BAO tower is a 300 meter tall lattice tower with a triangular cross-section, 10 feet on each side. It is equipped with 15 foot long booms on the northwest (extended at 334 degrees) and southeast (at 154 degrees) sides of the tower for instrument installation at multiple height levels.

LM installed MEASNET-calibrated Class 1 instruments at 100, 150, and 200m levels on both the northwest and southeast sides of the tower. At each measurement location an NRG Systems 5967 anemometer and a #200P wind vane were installed at the end of each retractable boom, an example of which, is shown in Figure 4.

Figure 4: Anemometer and vane on the northwest 150m boom on BAO.

2.3. Vertical Lidar Sites

Given that one of the goals of the overall project was to demonstrate the usefulness of the WindTracer to make measurements over a large field of data, it was necessary to place multiple vertical lidars around the project area to provide appropriate comparison information away from the tower. Three ZephIR 300 vertical lidar units were leased for this purpose. The three units were located, as shown in Figure 1, near the base of the BAO tower and at two additional sites in the area (ZephIR 372 to the north and ZephIR 373 to the west). The unit near the tower (ZephIR 375) would be used to show the correlation with the tower measurements, and the other two units would be used for comparisons with WindTracer data at remote sites. Each ZephIR unit was configured to make wind speed and direction measurements at 10, 39, 60, 75, 90, 100, 120, 150, 200, 250, and 300 meters above ground level.

Figure 5: ZephIR 375 located 125 meters west of the base of the BAO tower.

3. Data Results

A comparison of the VL data with the tower data serves to confirm that both devices suitably compare and therefore comparisons of WindTracer data with the remote VL data should be accepted as reasonable. The left column of Figure 6, shows the comparison between the ZephIR and anemometer/vane combination to be generally acceptable with slopes near 1 and R^2 values above 0.98.

3.1. Single-Doppler Comparisons

A 30 degree wide sector VAD vector retrieval algorithm is used for single-Doppler WindTracer analysis of the continuous scan PPI data. The predominant wind direction at BAO over the experiment period was from the west, which means the SRFWT was generally looking upwind (273 degrees to BAO) and the BFWT was generally looking in a crosswind direction (030 degrees to BAO). The results show that the comparisons with met data remain very strong in both cases. The center (BFWT) and right (SRFWT) columns of Figure 6 show the comparison between the single-Doppler wind speed (top) and direction (bottom) measurements. Notice that in both cases the average speeds for the entire period are within a few cm/sec of the met tower data and the slopes are within 0.6% of unity.

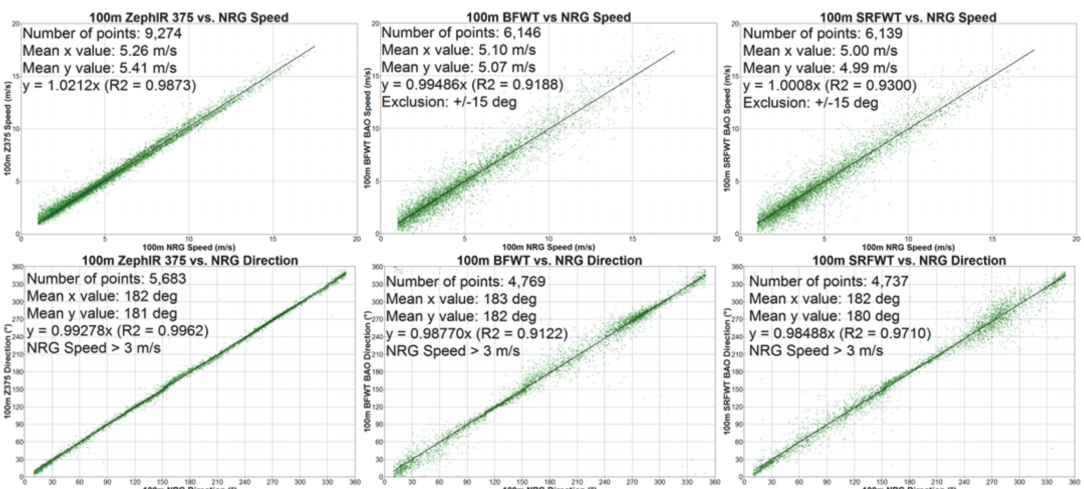

Figure 6: 100 meter tower comparisons. The left column shows ZephIR vs. tower data. The center (BFWT) and right (SRFWT) columns show the scanning-beam single-Doppler comparisons with the anemometer and vane set.

3.2. Scanning Dual-Doppler Comparisons

In addition to being able to compute single-Doppler wind vector retrievals from the PPI data, the data streams from the two systems can be combined for dual-Doppler analysis as well. During the PPI scan modes the scan patterns of the two WindTracer units were not tightly coupled meaning that the scanners were not necessarily pointed at the exact same point at the exact same time but the five-minute volumes did always begin within a few seconds each other.

Figure 7 shows the results of the scanning-beam dual-Doppler analyses at four sample locations. The first column shows the comparison with the tower anemometer and vane combination at 100 meters. The second column shows the comparison 100 meter level VL data near the BAO tower. The third column shows the comparison with the 100 meter data from the northern VL. The last column shows the comparison with the 100 meter data from the western VL. The top row shows the wind speed comparisons and the bottom row shows the wind direction comparisons.

In all cases the comparisons are very good with slopes close to 1.0 and R^2 values above 0.97.

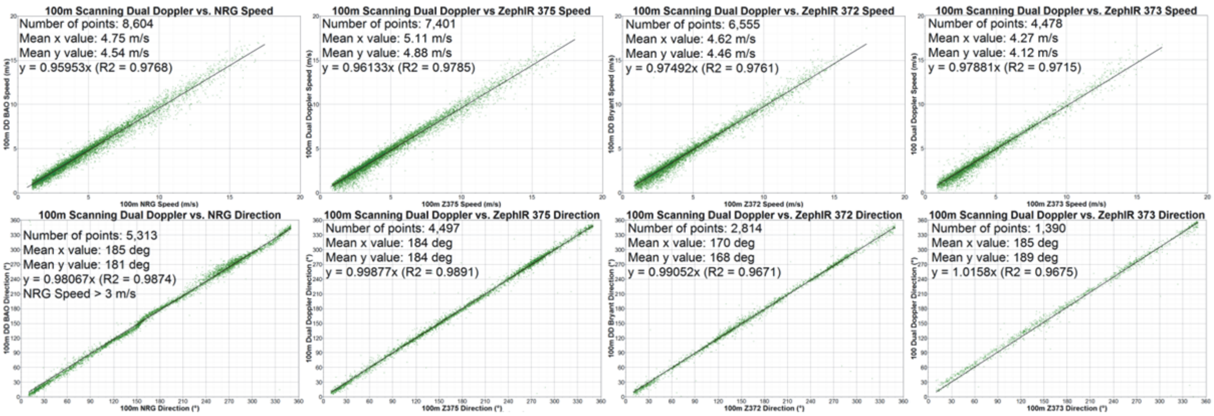

Figure 7: Scanning beam dual-Doppler comparisons. The top row shows speed comparisons, the bottom row shows direction comparisons. The columns show comparisons of dual-Doppler results to the anemometer/vane and three vertical lidars (BAO, northern, and western respectively).

3.3. Staring-beam Dual-Doppler Results

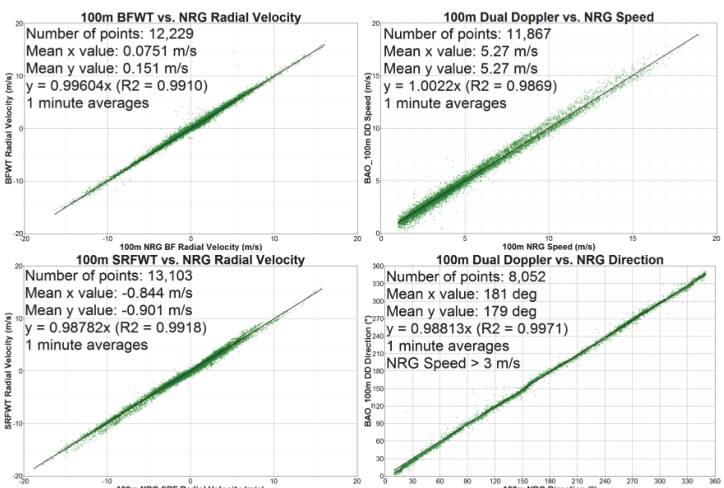

Figure 8: Staring beam dual-Doppler results. The left column shows the comparisons of the radial velocities measured by the two WindTracers (BFWT top, SRFWT bottom) compared to the computed component of the anemometer value. The right column shows the comparison of the dual-Doppler computed speed (top) and direction (bottom).

Figure 8 shows the comparisons of the staring beam dual-Doppler analysis. This data was taken during the last 10 minutes of each hour throughout the campaign. The data shown here is one minute average data. The left column of the figure shows the comparisons between the WindTracer reported radial velocities and the component of the anemometer speed in the direction of the individual WindTracer units. Comparison shows excellent correlations with slopes near 1.0 and R^2 values above 0.99. The right column shows the comparison of the results of the dual-Doppler measurements to the full anemometer and vane readings. Again, excellent correlations are noted with slopes very close to 1.0 and high R^2 values. These results are exciting as they demonstrate how staring beam dual-Doppler analysis can be used to make very accurate measurements of wind speed remotely and near existing structures such as towers or turbines.

4. Acknowledgments

This study has been funded by Lockheed Martin Commercial Ventures. The study leads would like to thank Ron Calhoun and Raghu Krishna of Southwest Renewables, and Julie Lundquist of the University of Colorado for their contributions to the field experiment design and for their on-going support. In addition, Greg Poulos of V-Bar, LLC gave helpful guidance at project conception. We are grateful to Clint Johnson, Taylor Geer, and Reesa Dexter of GL-Garrad Hassan, and Jerry Crescenti of Iberdrola Renewables who have provided review and guidance of the experiment design and are now engaged in review of the study results. Special thanks to Robert Carpenter at Campbell Scientific and to Michael Harris of ZephIR Lidar for help in supporting and interpreting the ZephIR vertical lidar data.