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Abstract. A field demonstration was done from Virginia Beach, Virginia, to show the use of high-energy (250-mJ) eyesafe Doppler lidar for measurements of offshore wind. The lidar is located onshore and pointed near-horizontally to reach a target area many kilometers away. In sample measurements, the lidar scan's hypothetical turbine is located 6 km away. For one beam elevation of interest, the horizontal wind vector is measured by scanning the beam in azimuth. The elevation can then be changed to profile the wind at many altitudes. An example measurement is shown in which wind vector is determined at six altitudes covering the height of a supposed turbine and above. In addition to the wind vector, wind shear is measured across a turbine blade span width. Over a two-week period in October 2011, range capability was found to vary from 4.5 to 17 km depending on weather and aerosol backscatter conditions. A comparison was made with an anemometer to validate the lidar's measurements. © 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: [10.1117/1.JRS.6.063562](https://doi.org/10.1117/1.JRS.6.063562)]

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1 Introduction

Wind over the oceans and large lakes is typically strong and steady, representing a rich source of renewable energy. To capture this energy, several offshore wind turbines and wind farms have been installed in Europe and China and are in planning stages in the United States. Wind measurements in the context of wind turbine energy production are relevant for several reasons. First, power generation is directly tied to wind speed. Second, wind direction determines the best rotational orientation of the turbine. Third, very strong winds, strong wind shear, or strong gusts can strain the structural integrity of a turbine.

While wind measurements are desired during cost-benefit analysis before turbine installation and during turbine operation, making such observations in an offshore environment at the heights needed can be difficult to implement. A meteorological tower to outfit with anemometers would be an expensive undertaking in a marine environment, especially so considering the tower height and underwater structural support needed to reach the ~150-m height of a turbine's upper blade span. Remote sensing of wind thus becomes an attractive option.

Doppler lidar is a remote-sensing technology that is under evaluation, such as lidar units positioned on buoys, structures, or ships in oceans and lakes.¹⁻³ These lidar solutions make use of pointing a beam upward to scan a conical pattern above the lidar. We investigate here an alternate geometry in which a high-pulse-energy lidar scans a target area from the side and from a long distance (kilometers) away. This side-scan geometry offers several advantages to an upward-looking lidar. First, the side-scan lidar can be positioned a long distance away from the turbine, such as onshore. Range capability of the lidar becomes an important factor in this regard. Second, one lidar can cover multiple target wind turbines spread over a wind farm that spans many kilometers. With a short laser pulse compared to the relatively slowly spinning

blades of a turbine, the lidar can make measurements through the blade span of a turbine to probe the area behind a turbine. Third, the side-scan lidar offers a better altitude resolution. This is allowed by using fine angular pointing in elevation to resolve altitude, rather than being limited in altitude resolution by a laser pulsewidth of several hundred nanoseconds. Fourth, a side-scan lidar is more accurate in wind speed measurements because the near-horizontal beam orientation is aligned with the horizontal wind of interest. With an upward-looking lidar, the elevation angle involves an orientation such that line-of-sight accuracy errors get magnified by 1 over the cosine of the elevation angle. In addition, an upward-looking lidar gets a strong component of vertical wind to create error in calculating the desired horizontal wind vector. Use of a side-scan geometry with the associated benefits has been shown for terrestrial wind power generation applications by Hannon et al.⁴ and Käsler et al.⁵ In this work, we show measurements over the marine environment with combined azimuth and elevation scanning (rather than a slice in either azimuth or elevation) and using a higher-energy laser transmitter.

The lidar used here is of a Ho:Tm:LuLiF laser, 2054-nm wavelength, 250-mJ pulse energy, 200-ns pulsewidth, 10-Hz pulse repetition rate, and 15-cm receiver aperture.^{6,7} A favorable feature of the lidar design is that its output is safe for viewing by the human eye. The lidar can be used in configurations, such as this experiment, where people may encounter the beam without a risk for eye injury. Nor is the beam visually distracting, due to its invisible infrared wavelength. The design and performance of the lidar has been described in previous publications, although the laser pulse repetition rate has been upgraded to 10 Hz from 5 Hz in the previously reported work. More recent work has been to ruggedly package the lidar and reduce its size for installation on an aircraft,⁸ though the lidar was used on the ground in this study.

2 Siting and Scan Geometries

To evaluate the lidar, we positioned it at a location in Virginia Beach, Virginia, overlooking the Atlantic Ocean and Chesapeake Bay, as shown in Fig. 1. This site is close to a proposed wind farm area and close to a land-based anemometer for comparison purposes. The lidar is housed within a mobile trailer, shown in Fig. 2, that was placed in a parking lot of the Joint Expeditionary Base Little Creek, Fort Story, Virginia. A beam scanner is attached to the roof of the trailer to direct the lidar beam to the desired orientation. With the parking lot surface 2.5 m above mean sea level and the beam scanner 3.5 m above the parking surface, the horizontal pointing of the lidar beam is 6 m above mean sea level.

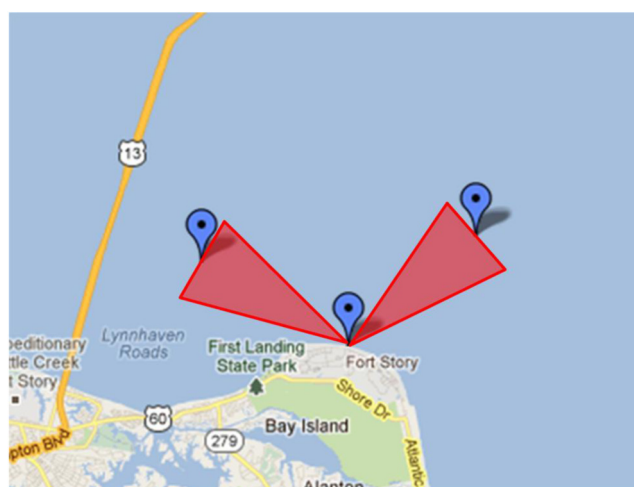


Fig. 1 Map of lidar location in Virginia Beach, Virginia, represented by the blue pin at Fort Story. A 30-deg azimuth scan was used to measure the horizontal wind vector. Scans were oriented in two directions—one looking toward the northwest into the Chesapeake Bay and one looking toward the northeast into the Atlantic Ocean. Hypothetical wind turbine locations at 6 km distance from the lidar are marked as blue pins. Map adapted from <http://www.google.com>.



Fig. 2 The lidar is situated in a mobile trailer laboratory, parked at the Joint Expeditionary Base Little Creek, Fort Story to overlook the Atlantic Ocean and Chesapeake Bay. A beam scanner is attached to the roof for steering the lidar beam. (Photograph courtesy of: NASA/Sean Smith.)

To calibrate the lidar beam viewing angles in azimuth (with respect to compass heading) and elevation (above horizontal), the beam was steered onto a hard target. The New Cape Henry Lighthouse, shown in Fig. 3, served as a convenient target owing to its height above surrounding trees. By knowing the location and height of the lighthouse and the location and height of the beam scanner, the azimuth and elevation of the lidar beam were calibrated. To verify elevation angle calibration, the lidar beam was steered to a downward angle (0.1 deg downward, for example) to strike the ocean surface many kilometers away. The measured range to the ocean surface, given the height of the beam scanner, served to verify the elevation angle as correct.

Doppler lidar measures speed of the wind along the line of sight being viewed, so to determine a horizontal wind vector, the lidar beam must be scanned in azimuth. With a wider scanning azimuth angle, the horizontal wind measurement will be more accurate because the beam probes a wider range of directions with which the horizontal wind will be aligned. However, this higher accuracy must be balanced with a consideration of the size of the area being scanned. The calculation of wind assumes that the wind is uniform over the area being scanned and uniform over the time needed to make the scan. As a balance between considerations of accuracy and assumptions of spatial wind uniformity, we chose to use a scan of 30 deg in azimuth. Three lines of sight were spread over this 30 deg, with a center line along the heading toward a target and 15 deg to either side. The 30-deg azimuth scan is shown in Fig. 1 in two different headings to profile the wind at two hypothetical turbine locations. An example wind measurement with such a 30-deg azimuth span (centered on a heading of 49 deg in this case) with a horizontal elevation is shown in Fig. 4. The wind speed increases with distance from shore to 5 km with a wind direction



Fig. 3 The New Cape Henry Lighthouse provided a target for calibrating the lidar beam scanning angles. The lidar was scanned over an anemometer for comparison of the two sensors' wind measurements.

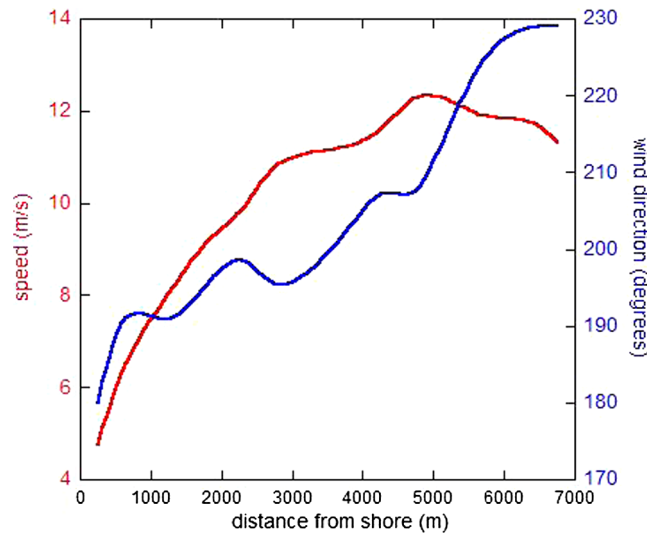


Fig. 4 Wind vector with distance from shore along a bearing of 49 deg. This heading brings the lidar beam out over the Atlantic Ocean. Data was taken on October 14, 2011, at 0100 pointing at a horizontal elevation angle, which puts the lidar beam at 6 m above the ocean surface.

moving from south to west. This example demonstrates that the onshore wind vector can be quite different from the offshore wind vector.

3 Range Capability

Range capability of the lidar depends on the aerosol content of the atmosphere, which is highly variable. The level of aerosol backscatter varies with season of year, geographic location, time of day, and weather patterns. From measurements dating back to 2005 from Hampton, Virginia (33 km inland from the Fort Story location of this experiment), aerosol backscatter is at a minimum in late fall and maximum in late spring. Hence, this experiment was done in a low-backscatter season of the year.

Over the period from October 4 to October 17, 2011, the farthest range from which a line-of-sight wind measurement could be made was checked using a 10-s (100 pulses) integration time and a horizontal elevation pointing at a heading of 49 deg (into the Atlantic Ocean). The minimum and maximum of the most distant ranges seen were 4.5 and 17 km, respectively, as shown in Fig. 5. The minimum occurred with an easterly wind bringing in clear air from over the ocean. This easterly wind had persisted for many days after the passing of a cold front. The maximum of 17 km occurred after a westerly wind was dominant for a few days. This westerly wind brought aerosol-rich air from land out over the ocean. Several days of rain were also encountered, including drizzle and heavy downpours. On rainy days, the minimum farthest distance seen was 6 km. A weather situation not encountered was fog, which would likely limit range capability.

A significant difference was observed in aerosol conditions of air over the ocean and air over land. In occasionally swinging the lidar beam heading alternately over the ocean and over land, a difference in backscatter signal level was observed ranging from 3 dB less to 10 dB less over the ocean than over land. The lower lidar backscatter conditions of the marine environment have been studied by Catrall et al.⁹

4 Wind Profiling over Turbine Heights

To measure wind at different altitudes, the elevation angle was changed. A configuration used to profile wind in the following data examples was for a target 6 km away with elevation angles of 0 deg, 0.42 deg, 0.90 deg, 1.37 deg, 1.85 deg, and 11.25 deg to probe altitudes of 6, 50, 100, 150,

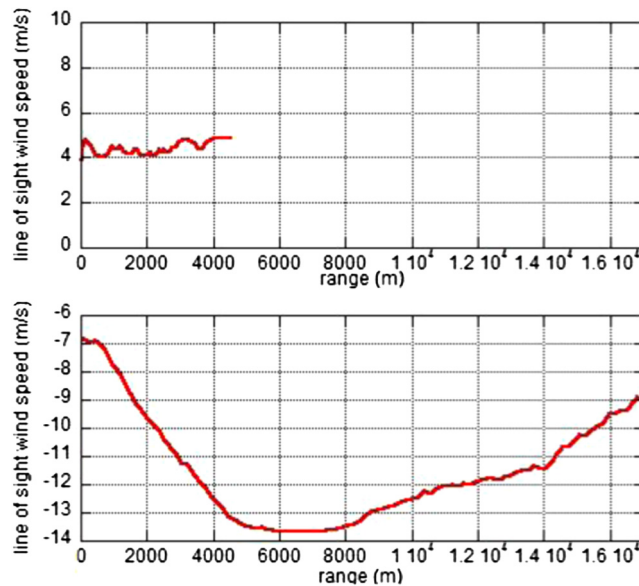


Fig. 5 Line-of-sight wind speeds on a bearing of 49 deg in cases of minimum (upper plot) longest range observed and maximum (lower plot) longest range observed over a 2-week observation period in October 2011.

and 200 m and the top of the atmospheric boundary layer. A scan pattern of three azimuths for each of the six elevations was repeated in an automated algorithm for continuous profiling over many hours. Each scan pattern of 18 lines of sight took 3 min to complete for pulse averaging, movement of the beam scanner, and data storage.

Results from such a scan pattern are shown in Fig. 6, composing the wind vector from lines of sight spread over 30-deg azimuth. In each line of sight direction, the wind was averaged over the measurements made of ranges of $6 \text{ km} \pm 500 \text{ m}$. A scan of a hypothetical turbine off to the northeast in the Atlantic Ocean was made, immediately followed by a scan off to the northwest for a hypothetical turbine located in the Chesapeake Bay. These wind profiles are shown next to a sketch of a supposed wind turbine of 100-m height and 50-m-long blades. The uppermost wind measurement of the figure, which shows the wind vector at the top of the atmospheric boundary layer, is not to scale with the five lower measurements. Throughout the altitude range of these measurements, the wind was generally WSW. An interesting point of this figure and throughout the data of the experiment period is that the wind did not vary as much over the ocean from near the surface to the top of the atmospheric boundary layer as is typically found over land. Examples can be seen in previous publications of land-based measurements in which the wind speed varies by many meters per second and wind direction varies over many tens of degrees from near the surface to the top of the atmospheric boundary layer.^{6,7}

Data in the format of Fig. 6, but concentrating on the one turbine location in the Atlantic Ocean, were recorded continuously to look at the wind vector trend over many hours. Figure 7 presents the observed wind vectors from 1230 on October 13, 2011, to 0830 the following day. To remove the effects of wind gusts, this data was rolling-averaged over 10 min. Trends seen in this data are wind speed peaking in the evening and early morning hours.

5 Wind Shear across Turbine Blade Span

Wind shear across the blades of a wind turbine can reduce the power output of the turbine and apply mechanical strain to the turbine structure.¹⁰ By comparing the wind vector at 50- and 150-m height of Fig. 7, a time trend of wind shear can be quantified across a supposed turbine blade span. The wind vector at these two heights is co-plotted in Fig. 8 for convenient viewing. Examining the wind speed over this time period shows that the two heights have a roughly

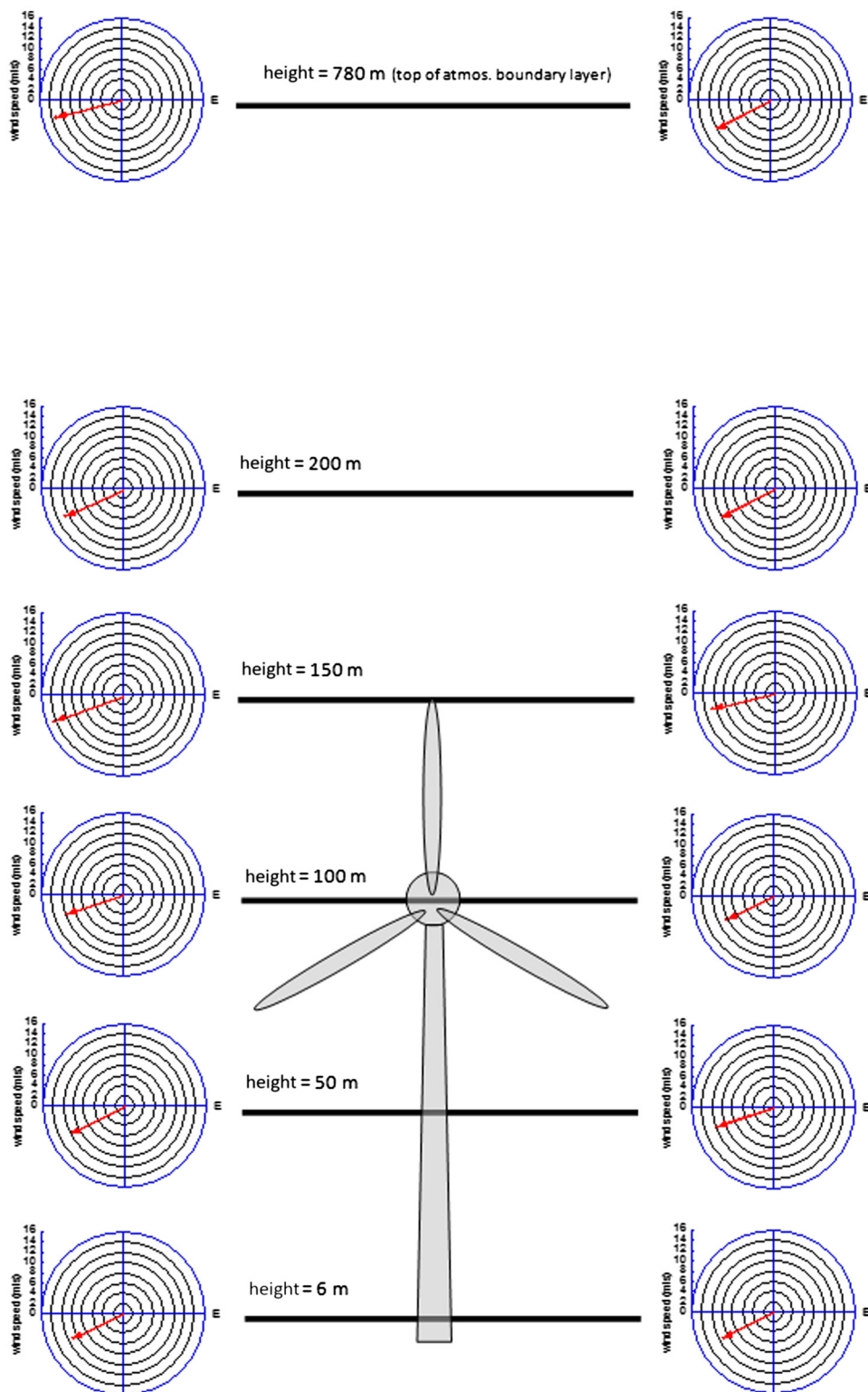


Fig. 6 Wind vectors measured at six altitudes to match the height of a supposed wind turbine of 100-m hub height and 50-m-long blades. Measurements were made in succession of a hypothetical turbine location 6 km toward the northwest in the Chesapeake Bay (left side of plot) and 6 km toward the northeast in the Atlantic Ocean (right side of plot). The lower five wind vector measurements are scaled to the turbine height. The upper plots are not to scale and are made to measure wind at the top of the atmospheric boundary layer.

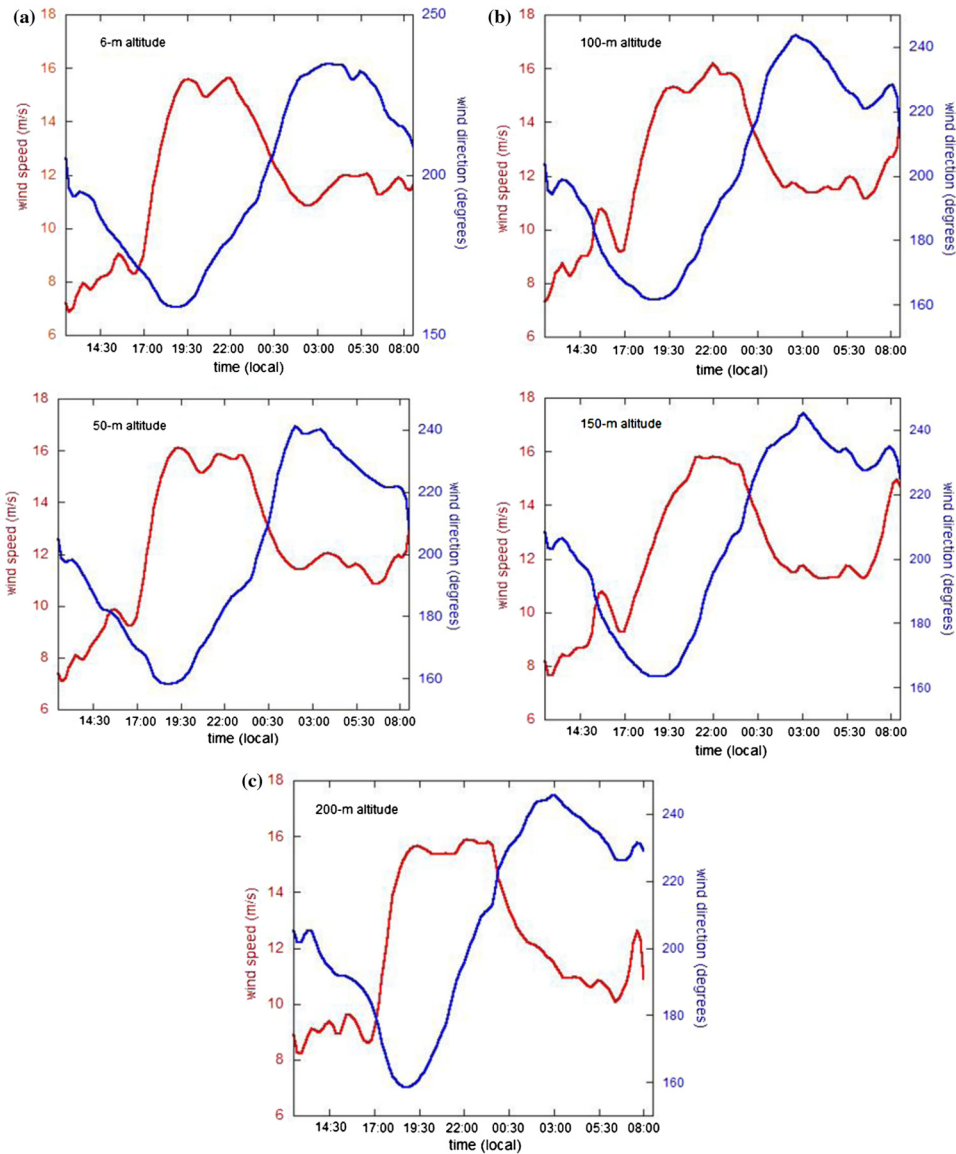


Fig. 7 (a), Wind vector time trend measured from October 13–14, 2011 at 6 and 50 m above the ocean surface. (b), Wind vector time trend measured from October 13–14, 2011, at 100 and 150 m above the ocean surface. (c), Wind vector time trend measured from October 13–14, 2011, at 200 m above the ocean surface.

equivalent speed over the course of a day except for several hours after sunrise and sunset. The maximum difference in wind speed observed at these two heights is 2.4 m/s. Taking the definition of the shear exponent as,

$$\alpha = \frac{\ln\left(\frac{s_2}{s_1}\right)}{\ln\left(\frac{h_2}{h_1}\right)},$$

where s_1 and s_2 are the speeds at heights h_1 and h_2 , respectively, gives the maximum observed value of shear exponent to be $\alpha = 0.15$. This level of shear is lower than that documented in studies of typical diurnal variations of wind speed shear over land, presumably because vertical gradients in speed over the ocean are less steep than over land.¹¹ Wind direction can also create a shear, which can be seen in Fig. 8. The wind direction trend shows a constant offset toward counterclockwise rotation of direction at 150-m height from 50-m height. The largest difference seen in wind direction is 17 deg.

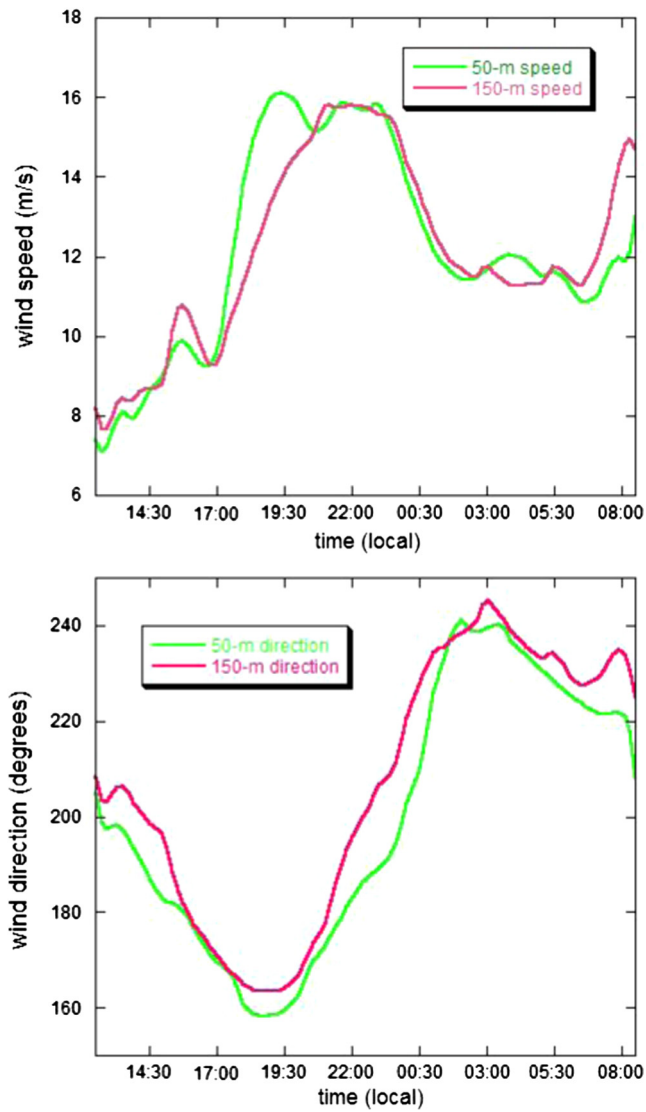


Fig. 8 Wind vector time trend at altitudes corresponding to a hypothetical wind turbine blade span. Instances of shear can be seen in both speed and direction.

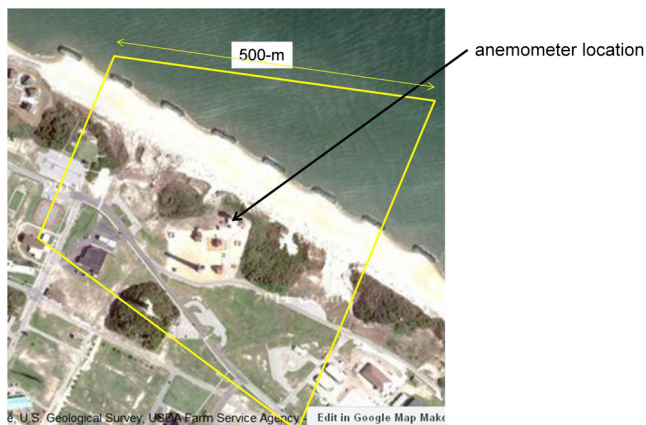


Fig. 9 Overlap of lidar scan pattern and anemometer. The lidar scans (outlined as a yellow trapezoid) a 30-deg azimuth centered over the anemometer location. Map adapted from <http://www.google.com>.

6 Anemometer Comparison

To compare lidar results with another sensor, the lidar beam was scanned around an anemometer fixed to the top of a building, as shown in the photograph of Fig. 3. The scan pattern used was also a 30-deg azimuth scan like that used for scans over hypothetical turbine sites. To intercept the 25.9-m height of the anemometer located 913 m from the lidar, the lidar's beam was tilted at 1.25-deg elevation. Along each line of sight, speeds were averaged over 250 m to either side of the anemometer location. The lidar is thus averaging a trapezoidal area centered on the anemometer position, as diagrammed in Fig. 9. Lidar measurements were made over the anemometer location for approximately 1 h on several different days to capture different wind and weather conditions. With the lidar taking 30 s for a measurement and the anemometer reporting 5-min averages, the root mean square difference between the two sensors was 1.2 m/s in speed and 6.8 deg in direction. This represents a good level of agreement, considering that each sensor is sampling a different area: the *in situ* anemometer is taking measurements at a point, whereas the lidar is averaging over an area. Other comparisons with lidar and an anemometer have produced similar results.⁴

7 Conclusion

We have shown that high-energy Doppler lidar can measure wind fields over heights of interest to wind energy production with the sensor placed a distance of many kilometers away from a target. This long stand-off distance is useful in offshore wind measurements in that the lidar can be placed at a convenient onshore location. By adjusting the elevation angle of the lidar beam, different target heights can be probed, such as covering the sweep area of a wind turbine. By adjusting the azimuth angle of the lidar beam, different target locations can be probed such as multiple wind turbines spread out over a wind farm area.

A scan pattern was devised of a 30-deg sweep in azimuth to make a measurement of the horizontal wind vector. Sample data was taken over many hours at six elevation angles to measure the wind at six altitudes over a target located 6 km away from the lidar. Lidar performance in the marine environment was tested over a 2-week period to find significant variations of aerosol backscatter. The range capability of the lidar for a 10-s integration time varied from 4.5 to 17 km over a 2-week time period in October 2011, with the minimum occurring after multiple days off steady wind from over the ocean. Range capability is a critical parameter in use of the lidar, as it determines how far away the lidar can be placed from the target area. A seasonal variation in range capability is suspected, as aerosol conditions change throughout the year.

With the capability of the lidar shown to offer relevant measurements for offshore wind energy production, future work to consider includes several possibilities. First, the lidar could be used to create a record of wind measurements over the course of a year. This database would be of value for a cost-benefit analysis for building an offshore wind farm. Extreme wind events of strong storms, hurricanes, and gusts could be characterized to provide the designers of wind turbines with an indication of wind loading that can be encountered by the turbine. Second, the lidar could be setup to overlook an actual wind turbine installation to correlate turbine output power with wind observations. Third, the lidar could be used to provide a wind farm with real-time information on the wind vector so that turbines could be optimally rotated into the wind or to provide a warning of severe wind events that could damage a turbine.

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Paul J. Petzar graduated from Bucknell University in 2004 with a BS in electrical engineering, and was a Langley Aerospace Research Summer Scholar at NASA Langley, in 2002 and 2003. He began his professional career as a contractor with SAIC at NASA Langley and moved to Hampton Roads permanently. He worked in the Laser Systems Branch, developing laser controlling electronics. In 2006, he became a contractor with the NIA. In 2010, he became a civil servant and is in the Electronics Systems Branch. His current project is SAGEIII on ISS, a flight project developing an external payload for the ISS to launch, in 2014.

Michael J. Kavaya has worked on coherent-detection pulsed lidar for over 30 years, with an emphasis on wind measurement. He received a PhD in EE from Caltech. He began his career at NASA/JPL with a CO₂-coherent lidar studying aerosol backscatter. He developed a technique to calibrate the lidar's measured aerosol backscatter coefficient using a calibrated hard target. He then joined Coherent Technologies, Inc., and developed the first solid-state coherent Doppler wind lidar at 1 micron and the first eyesafe version at 2 microns. He then joined NASA/MSFC to work on measuring winds from space with a CO₂-coherent lidar, later transferring to NASA/LaRC to continue pursuing the space wind mission using LaRC's record-high-energy, 2-micron laser. At LaRC, he has advanced the space mission through leading technology advancement, compact packaging, theory, parameter tradeoff studies, space mission computer simulation, aircraft instrument development and flight, space mission designs, and mission education and advocacy.

Biographies and photographs of the other authors are not available.