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Abstract

Our research team engaged in the validation of a Laser Wind Sensor (LWS) unit scheduled for later deployment in Lake Michigan. This was done through comparison with wind speed measurements made by anemometer cups mounted on a traditional meteorological tower on land against those made by the LWS mounted on a flowing platform in Muskegon Lake about 423m away. Because these two gauges are not co-located and may not always be measuring the same wind, the paired-*t* method was employed to study the series of differences in wind speed measurements with differences less than 0.1 m/s the considered to be not operationally significant. Wind speed was measured each second and ten-minute averages computed and used in the analysis. The average differences for wind speed less than 6.7 m/s at the cup anemometers were found to be not operationally significant. The same result was obtained for higher wind speeds not during storms. Data from storm periods is still under study. A prior study comparing two other LWS units, one land mounted and the other on the same type of floating buoy platform, was extended using the paired-*t* methods. Results confirmed that the only differences in 10-minutes average occurred during periods of different wind direction at the two gauges validating the motion compensation features of the Laser Wind Sensor unit. The buoy was deployed at Lake Michigan's mid-lake plateau, 35 miles from shore in 45 m of water, for the 2012 field season. Analysis of those data is ongoing.

Introduction

Wind resource assessment is a critical initial step toward a successful wind energy project. For decades, the industry has relied on meteorological ("met") masts with cup anemometers to record wind speed and direction. While met masts are relatively easy to install on terrestrial sites, installation at offshore locations can be prohibitively difficult. Offshore met towers range in price from $2.5 million for installation in relatively shallow water (e.g. Cape Wind, Massachusetts) to more than $10 million for one in deeper water up to 30 m (e.g. FINO 1, Germany) [1]. Met towers in water in excess of 30 m may not be cost effective. Fixed met masts cannot be easily moved to support other projects. In many cases, a fixed platform requires permits and/or bottomland leases from regulatory authorities. Obtaining such permits can be a lengthy process. As turbines increase in hub height, building a met tower to support such hub-height measurements becomes more costly and difficult.

As project developers evaluate constructing taller turbines in deeper waters, they are considering alternative resource assessment technologies. The US National Buoy Data Center operates a network of anemometer-equipped buoys. These buoys, however, measure wind speeds at 5 m above the water surface and are unsuitable for wind energy resource assessment [2]. Dedicated platforms and sensors will be required to support offshore wind energy development.

In its report *Large Scale Offshore Wind Power in the United States*, the National Renewable Energy Laboratory noted a need for tools that can measure wind speeds at multiple locations and determine wind shear profiles up to hub height. The report authors also identified a need for stable buoy platforms to support the aforementioned assessment tools [2]. Of course, the cost needs to be less than that of a similarly equipped met tower.

A number of remote sensing technologies have emerged as potential alternatives to tower-based cup anemometers, such as light detection and ranging (LiDAR), sound detection and ranging (SoDAR) and airborne synthetic aperture radar (SAR) sensors [3] (Hasanger et al. 2008). LiDAR and SoDAR operate similarly in that a signal (light or sound of a particular frequency) is emitted by the unit, the signal reflects off dust particles in the atmosphere, and the sensor captures and records the return signal. As the signal reflects of the moving dust particles, its frequency decreases (the Doppler effect). As wind speeds increase, so do the speeds of atmospheric particles. A large decrease in signal frequency is associated with faster wind speed [3].

The accuracy of LiDAR systems has been tested against met masts in onshore and offshore settings. Hasanger et al. [4] reported results from three validation experiments in Denmark. At the Horns Rev site, LiDAR measurements were compared to three met masts at 63 m and found a high level of agreement (R^2 = 0.97-0.98). Lang and McKeogh [5] reported high levels of agreement at heights up to 80 m between LiDAR and met mast anemometers (R^2 = 0.97) and for SODAR as well (R^2 = 0.98-0.99). The measurement bias ranged from 0.12-0.15 m/s. LiDAR and anemometer measurements from the FINO platform also showed a high level of agreement (R^2 = 0.99) and a bias of -0.15 m/s to 0.08 m/s at heights from 70 m to more than 100 m [6]. Kindler and colleagues also demonstrated the validity of LiDAR measurements in onshore and offshore settings [7]. These and other verification studies show that remote sensing of wind speeds using LiDAR produces results nearly identical to those of a traditional met tower.

Remote sensing technologies such as LiDAR and SODAR depend on accurate measurements of Doppler shift. Terrestrial LiDAR sensing applications are relatively straightforward and the LiDAR unit is placed on flat ground or fixed to a platform. Moving platforms, such as on a ship or buoy, have been shown to induce errors in measurement, including errors in speed due to the units velocity or tilting [8]. Pichugina et al. [9] were among the first to document the use of shipboard LiDAR sensors with motion compensation. Their preliminary error propagation model (not a true validation) suggested a wind speed precision of less than 0.10 m/s for 15-minute averaged data. The authors noted that "work is needed, perhaps involving comparisons with lidars or tall towers mounted on a fixed offshore platform, to establish how closely the shipboard HRDL [LiDAR] system approximates the high precision that is obtainable during land based observations" [9, p. 334].

All of the LiDAR validation studies to date have used ground-based LiDAR units or those mounted on a fixed platform at sea. As such, the LiDAR unit and the gage against which it was validated (cup anemometer or another LiDAR unit) were measuring the wind in the same location and at the same height. The commonly used measure of comparison was the correlation coefficient r or the coefficient of determination R^2.

None have yet validated a LiDAR sensor mounted on a buoy or other stable, floating platform. A floating platform introduces wave motion that could affect wind measurement and must be compensated for. Regarding remote sensing units on floating platforms, the National Renewable Energy Laboratory report made the following suggestion.

> To gain enough confidence for these systems to replace the conventional met mast, a large amount of experience with commercial projects at sea will be needed. This will require, in turn, close cooperation among private technology companies, offshore developers and operators, and government R&D programs at the US Department of Energy (DOE) and BOEM [Bureau of Ocean Energy Management], both in terms of taking the data and verifying the results. Once a reliable and proven track record has been established, the improved accuracy for wind and energy production measurements will remove a significant amount of risk from developers [2, p. 65-66].

In this case, the gauge against which the LiDAR unit is compared may not be mounted on the same platform. For example, a cup anemometer may be mounted on a met tower on land nearby. Furthermore, it may be the case that the LiDAR unit and the comparison gauge, which may have existed before the LiDAR unit was located nearby, are not measuring wind at the same height. Thus, it is not reasonable to assume that the LiDAR unit and comparison gage are not measuring the same wind. This brings into question the use of a single measure of comparison such as r or R^2 but rather leads to the idea that some way of understanding the differences in measurements made by the two gauges over time must be employed.

The research team at Grand Valley State University (GVSU), in collaboration with researchers from the University of Michigan and Michigan Natural Features Inventory (MNFI), has extended the LiDAR validation process. GVSU solicited an open proposal for gathering offshore wind data on the Great Lakes. GVSU received 3 responses:

- A fixed MET tower estimated to cost between $6 and $10 million;
- A floating MET tower estimated to cost $5-$6 million;
- A floating buoy platform with LIDAR estimated to cost $1.5 million.

GVSU selected the AXYS WindSentinel, a NOMAD floating buoy platform with Vindicator Laser Wind Sensor technology, based on cost and flexibility. In 2011, GVSU used funds from the DOE and other partners to purchase the WindSentinel.

The WindSentinel's floating platform is commercially available but has not yet been validated against a met tower. The team's initial, primary research goal was to validate the accuracy of the buoy-mounted laser sensor. By validate, we mean shown to be reliable in collecting data that can be used for decision making. In this case, obtaining data that can be used to estimate the potential value of the wind energy in Lake Michigan. Validating the sensor's operation in field trials could pave the way for lower cost, reliable offshore wind resource assessment in multiple locations where metrological towers was not feasible due to cost or water depth. This study includes the first deployment of a laser wind sensor over water and the only currently planned deployment in a lake or inland sea.

The laser sensor and buoy platform

The WindSentinel buoy was equipped with Vindicator laser wind sensor (LWS). The Vindicator, made by Catch the Wind, Inc., uses a type of pulsed LiDAR to record wind speed and direction at 3-6 range gates from 50 m to 150 m [10].

The floating platform is a six meter NOMAD (Navy Oceanographic Meteorological Automatic Device) buoy. The buoy accommodates a full complement of sensors and power supply options. In addition to the Vindicator LWS, the WindSentinel is equipped with bird and bat acoustic detectors, water quality sensors, standard meteorological sensors, and sensors for measuring wave height, direction, and period [11].

The NOMAD buoy's wave sensors are a critical component to the WindSentinel operation because wave motion can affect the measurements made by the LWS. The WindSentinel records the wave data and applies a proprietary algorithm to compensate for the motion of the buoy by adjusting the raw measurements. The result, in theory, is the equivalent of a stable platform for reliably measuring wind speeds at hub height.

The array of sensors aboard the WindSentinel requires a substantial power supply. The buoy is powered by a redundant system of solar panels, a small wind turbine, and a diesel generator, all of which are integrated into a battery bank [11] (Figure 1).

Figure 1: The wind monitoring buoy on site in Muskegon Lake. The egg-shaped device mounted above the deck is the Vindicator laser wind sensor. The kayak offers a sense of scale.

Validation strategy

The first validation step is to compare measurements made by co-located LiDAR and met masts with cup anemometers. Such studies have been well-documented in the literature [3-8]. These validation studies consistently show that LiDAR wind sensors produce wind speed and direction measurements that are nearly identical to those of tower-mounted anemometers. In the present study, we assumed that previous work sufficiently demonstrated the laser sensor's validity as compared to co-located, fixed platforms.

The study described here focused on comparing fixed and buoy-mounted LiDAR units as well as comparing buoy-mounted LiDAR with a met mast mounted anemometer. The former determines the effectiveness of motion compensation technology while keeping constant the measurement tool. The latter helps determine the utility of a LWS unit as a data gathering tool for energy potential determination studies.

As previously discussed, the goal of this study is to understand the differences in time of the measurements made by a LWS unit mounted on a floating buoy and either a second LWS or cup anemometers mounted on a met tower on the shoreline about 400 – 700 meters away. Average differences of less than 0.1 m/s, were considered insignificant for our purposes. This value is the smallest non-zero measurement made by either gauge. The statistical significance of the average difference compared to zero was also determined.

Validation experiments

Comparing fixed and buoy mounted laser sensors

In 2010, buoy manufacturer AXYS Technologies field tested the WindSentinel buoy at Race Rocks, British Columbia [unpublished data]. Measurements from the buoy mounted laser wind sensor (LWS) were compared to measurements from an identical LWS located on a small island (Land Station) about 700 m away. AXYS Technologies provided the research team with the field-collected data. The range gates were set with centers at 100 m, 150 m, and 200 m for each LWS.

Observations were made at one-second intervals. Using industry standards, 10-minutes averages were computed from these observations. Any 10-minute average observation that consisted of fewer than 300 one-second observations (50%) was eliminated, leaving 3022 observations of wind speed and corresponding wind direction.

The series of differences in these averages between the gauges was computed using the following formula.

$$Difference_t = WindSentinel_t - LandStation_t$$

Large differences in wind speed correlate in time with large differences in wind direction indicating that at certain times the winds measured by the Wind Sentinel and Land Station were different. Some left-side skewness with long tails were noticed in the histograms for all range gates (Figure 2). The long tails may be due to these high speed differences.

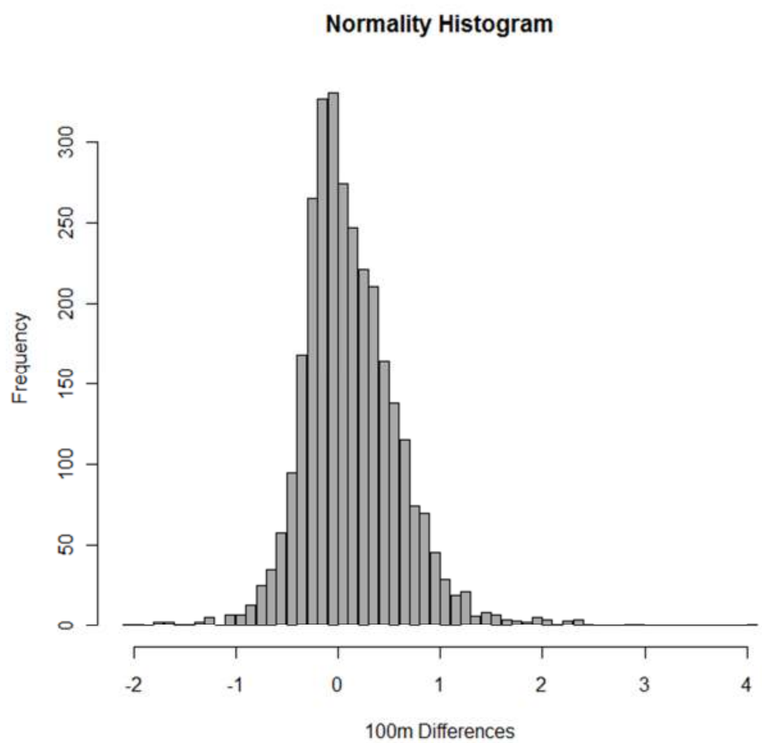

Figure 2. Normality histogram for the 100 m range gate. Histograms for other range gates were similar.

Results from the paired *t*-test (Table 1) indicate that the mean differences for the 150 m and 200 m range gates were less than 0.1 and therefore not operationally significant. The mean difference, however, for the 100 m range gate was 0.13 m/s. The difference, strictly speaking, is operationally significant, but small and is of the order of 0.1 m/s. The mean differences for all three range gates were statistically significant, an indication of low variance in the difference values.

Table 1: Paired *t*-test results for the Race Rocks data.

Range gate	**Mean Difference (m/s)**	**Standard Deviation (m/s)**	**Number of differences (*n*)**	***p*-value**
100m	0.1301	0.4812	3022	2.2e-16
150m	0.0761	0.4838	3022	2.2e-16
200m	0.0740	0.4787	3022	2.2e-16

The experiment shows that there is no meaningful difference in operation between the buoy-mounted laser sensor and the sensor on the island, particularly for the 150 m and 200 m range gates. Given the 700 m distance separating the two sensors, it is plausible that the observed operational difference at the 100 m level is attributable to actual differences in wind conditions, particularly the wind direction differences noted when large differences in wind speed were observed. This experiment provides validation evidence concerning the NOMAD buoy's motion compensation system and its application in laser wind sensing.

Comparing buoy-mounted laser sensor and met mast measurements

The next experiment compared the measurements made by the LWS unit mounted on the buoy to those made by cup anemometers mounted on a met mast on the shore line.

The WindSentinel buoy and Vindicator laser wind sensor used for this experiment are not the same items used in the Race Rocks experiment. The technology, however, is the same as that used in the Race Rocks experiment.

Buoy and met mast locations

Grand Valley took possession of the WindSentinel buoy in September 2011 and deployed it in Muskegon Lake from 7 October 2011 to 3 November 2011. The buoy was positioned about 400 m offshore from a 50 m onshore met mast at the east end of the Muskegon Lake (Figure 3). The location of each sensor was as follows:

Figure 3. Location of the met mast and WindSentinel buoy in Muskegon Lake, Michigan, USA.

Sensor	Site	Coordinates	Elevation (AMSL)	Sensor height above lake level
Laser sensor	Muskegon Lake	43° 14' 55" N; 86° 14' 55" W	176 m	57.85 m
Met mast	Open field	43° 14' 46" N; 86° 14' 41" W	178 m	50.5 m

The Vindicator laser sensor employed in this experiment had six range gates, the lowest of which was at 55 m above the lens. The sensor was mounted on the buoy an additional 2.85 m above the lake level. The corrected Vindicator lens height for the lowest range gate was 57.85 m above the surface of Muskegon Lake.

The onshore met mast contained two calibrated (ISO/IEC 17025:2005) cup anemometers (NRG #40C). Both anemometers were located at 48.5 m above ground level with one anemometer facing northwest and the other southeast. The maximum wind speed of the two anemometers was used for the data analysis. Using the maximum, as opposed to the average, eliminates any erroneous data due to either A) one anemometer entering a failure mode; or B) differences in speed measurements due to differences in wind direction. The met mast site was 2.0 m above the lake level. This put the anemometers an effective 50.5 m above Muskegon Lake.

Thus, the laser sensor and cup anemometers measured wind speeds at slightly different heights (57.85 m and 50.5 m) and at locations 423 m apart. Like the Race Rocks analysis, these conditions are likely to reduce the observed agreement between the two gauges. We assert, however, that the acceptable level of agreement is that within the measurement error of the devices (operational significance, <0.1 m/s).

One-second (1 Hz) wind observations from were collected from 7 October 2011 through 3 November 2011. Ten-minute average wind speeds were computed for non-overlapping periods.

Wind observations and dataset partitioning

We hypothesized that the two gauges were measuring, to a reasonable degree, the same wind and thus would observe the same wind speed values. For each 10-minute period for each gauge, an average wind speed was computed from the observations made each second. The hypothesis can be tested by studying the series of differences computed as:

$$Difffference_t = MetMast_t - LWS_t$$

Recall that $MetMast_t$ is the maximum of the wind speed averages for the two anemometers. *LWS* refers to the buoy-mounted laser wind sensor. Table 2 shows the number of observations by classification.

Table 2: Number of observations by classification

Classification	Number of Observations
Total number of observation periods	3849
Number of missing observations	385
Number of non-missing observations	3464
Percent of non-missing observations	90.0%
Number of invalid observations	270
Number of valid observations	3194
Percent of valid, non-missing observations	92.2%
Number of outliers	1
Number of observations used in study	3193
Number of observations used in study / Number of observation periods	83.0%

The laser sensor reported about 10% of the observations as missing. An invalid 10 minute average, according to the industry standard, is one in which more than 300 of the possible 600 one-second observations were missing. There was one extremely large wind speed value that could not be explained and was thus considered an outlier. Thus, 83.0% (5 of 6) of the 10-minute averages were considered useable for analysis, well above the industry standard of 60% to 70%.

A graph of the 3193 pairs of 10-minute averages used in the study is shown in Figure 4. The observations made by the two devices track each other well. Some differences are noted at higher wind speeds. The blue line is data from LWS #8 (hws55) and the purple line is the data from the met mast anemometer (max48).

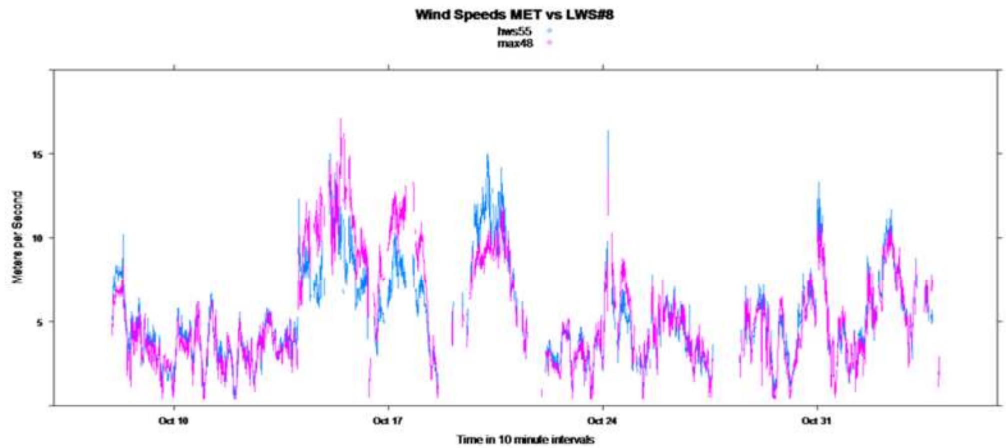

Figure 4: A comparison of wind speed measurements from the two devices. The blue line represents data from the LWS ("hws55") and the purple line represents data from the met mast anemometer ("max48").

The dataset was partitioned into two subsets based on the wind speed measured by the cup anemometers on the met mast: ≤ 6.7 m/s and > 6.7 m/s. This was done using a windowing technique with window size of one hour. If average wind speed for the current point in time and the next 5 points in time for the 10-minute averages was > 6.7 m/s, then all six 10-minutes averages in the window were assigned to the > 6.7 m/s dataset. The next 10-minute average considered is the one immediately following those in the window. Otherwise, the current 10-minute average is assigned to the ≤ 6.7 m/s data set and the next 10-minute average in time sequence is considered. Table 3 shows the number of observations in each data set resulting from this partitioning.

Table 3: Number of observations in the dataset.

Classification	**Number of Observations**
Number of observations used in study	3193
Number of observations ≤ 6.7 m/s	2149
Number of observations > 6.7 m/s	1044
% of observations ≤ 6.7 m/s	67.3%
% of observations > 6.7 m/s	32.7%

Analysis of the <6.7 m/s dataset

The average difference in measurements between the LWS unit and the met mast cup anemometers was -0.096 m/s with standard deviation of 0.58 m/s. The mean difference was less than 0.10 m/s (the precision of the gauge) and therefore not operationally significant. The difference was statistically significant (p<0.05). The validation evidence for the buoy-mounted laser wind sensor is obtained for wind speeds less than or equal to 6.7 m/s.

Analysis of the > 6.7 m/s dataset

The analysis of the > 6.7 m/s dataset was performed in two parts: observations that were windy but not stormy, and observations during three storm periods. Most LiDAR validation studies remove observations made under rain conditions from the dataset. During highly turbulent storm events, the wind speeds and direction as measured by the devices, which are separated by 400 m, are likely to be very different. Thus, we chose to analyze the storm data separately. This kind of data partitioning is consistent with other validation studies [12].

The paired t-test for the >6.7 m/s (but not stormy) dataset indicated that the mean difference (SD) was -0.03 m/s (1.09) and was below the threshold for operational significance. The difference also was not statistically significant ($p > 0.05$, $n = 416$). Because the mean difference was not operationally significant or statistically different from zero, we concluded that the buoy-mounted laser sensor and the met mast produced comparable results for times when the wind speed exceeded 6.7 m/s but were not stormy.

Future Work

With the validation completed, the buoy was towed to a location four miles offshore in Lake Michigan. The buoy recorded wind speed and direction, as well as other wave and meteorological data, for an abbreviated deployment from 4 November 2011 to 31 December 2011. Preliminary analysis of these data show median wind speeds of 9.4 m/s, 9.4 m/s, and 9.3 m/s at the 90 m, 110 m, and 120 m range gates, respectively. On 7 May 2012, the buoy was deployed at Lake Michigan's mid-lake plateau. This location is 35 miles from shore near the Michigan-Wisconsin border and has a water depth of about 45 m. The buoy will collect data on site until late fall 2012. Analysis of the Lake Michigan field data, as well as the storm data from the Muskegon Lake trial, is ongoing.

Summary and Conclusion

Remote sensing of wind speed using LiDAR has been validated and reported in the literature using co-located LiDAR and met masts mounted cup anemometers. The experiments reported here extend the validation to buoy-mounted LWS units. This is the first time that a floating LWS unit has been validated against cup anemometers mounted on a met mast on shore in the peer-reviewed literature. The Race Rocks experiment showed that two LWS units, one buoy-mounted, the other on a small island, produced wind speed measurements that were not operationally different (<0.01 m/s for 150 m and 200 m range gates). This effectively validated the LWS's motion compensation technology.

The validation was further extended by comparing the buoy-mounted laser sensor to an onshore met mast cup anemometer. For wind speeds at anemometers of 6.7 m/s or less, no operationally significant differences were found. The same is true for wind speeds > 6.7 m/s in the absence of storms. Thus, validation evidence for the buoy-mounted laser wind sensor is obtained: the buoy mounted laser sensor is as accurate as the anemometer under a variety of wind conditions, with the exception of storms, for the purpose of assessing wind energy potential in Lake Michigan.

In order to accomplish the validation task, new methods were needed as the LWS unit and the met mast were not co-located nor taking measurements at the same height and thus were not observing the same wind. This could often be the case as North America currently has very few offshore met masts that would be suitable for such a study. Lake Erie, off the coast of Cleveland, Ohio, and Nantucket Sound, Massachusetts, are two possible locations.

Thus a single measure of comparison, the correlation coefficient or the coefficient of determination, was not adequate. Instead, we computed a time-series of differences of 10-minute average values to study. An average difference of 0.1 m/s or less was deemed to be not operationally significant. A paired *t*-test was used to determine statistical significance of the average difference from zero.

Offshore wind energy development, particularly in deep water, will require new resource assessment tools and technologies. The WindSentinel buoy, and potentially other floating remote sensing systems, has the potential to deliver reliable, consistent, and cost-effective wind resource measurements capable of use at a variety of locations inaccessible by met tower technology by using a floating platform and a laser sensor.

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Literature Cited

[1] Wissemann, C. IOOS Offshore Wind energy Meeting presentation. Rutgers University, 2 February 2009. Available at http://marine.rutgers.edu/cool/coolresults/2009/ioos_020209/. Accessed 15 May 2012.

[2] Musial W, Ram B. Large-scale offshore wind power in the United States: Assessment of opportunities and barriers. National Renewable Energy Laboratory Technical Report. NREL/TP-500-40745, 2010. 221 pp.

[3] Hasanger C, Peña A, Christiansen M, Astrup P, Nielsen M, Monaldo F, Thompson D, Nielsen P. Remote sensing observation used in offshore wind energy. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 2008 1(1): 67-79.

[4] Hasanger C, Badger M, Peña A, Badger J, Antoniou I, Nielsen M, Astrup P, Courtney M, Mikkelsen T. Advances in offshore wind resource estimation. In *Advances in Wind Energy Conversion Technology* 2011, Matthew S, Philip G (eds), 85-106.

[5] Lang S, McKeogh E. LIDAR and SODAR measurements of wind speed and direction in uplant terrain for wind energy purposes. *Remote Sensing* 2011 (3); 1871-1901.

[6] Westerhellweg A, Canadillas B, Beeken A, Neumann T. One year of LiDAR measurements at FINO1-Platform: Comparison and verification to met-mast data. 10th German Wind Energy Conference DEWEK 2010. Available at http://www.dewi.de/dewi/fileadmin/pdf/publications/Publikations/S01_3.pdf. Accessed 15 May 2012.

[7] Kindler D, Oldroyd A, MacAskill A, Finch D. An eight month test campaign of the Qinetiq ZephIR system: Preliminary results. Meteorologische Zeitschrift 2007, 16(5); 479-489.

[8] Wolken Möhlmann G, Lilov H, Lange B. Simulation of motion induced measurement errors for wind measurements using LIDAR on floating platforms. Poster at 15th International Symposium for the Advancement of Boundary-Layer Remote Sensing (ISARS), Paris, France, 28-30 June 2010. Available at http://www.isars2010.uvsq.fr/images/stories/PosterExtAbstracts/P_WIN08_WolkenMohlmann.pdf.

[9] Pichugina Y, Banta R, Brewer W, Sandberg S, Hardesty R. Doppler lidar–based wind-profile measurement system for offshore wind-energy and other marine boundary layer applications. *Journal of Applied Meteorology and Climatology* 2012, 51; 327-249.

[10] Catch the Wind, Inc. 2010. Vindicator optical wind sensor: product overview. Web site. Available at http://www.catchthewindinc.com/node/293/specs. Accessed 15 May 2012.

[11] AXYS Technologies Inc. Wind Sentinel™ Offshore wind resource assessment buoy. AXYS Technologies, Sydney, BC, 2012. Available at http://www.axystechnologies.com/Portals/0/Brochures/WindSentinel%20digital%20Data%20Sheet.pdf.

[12] Peña, A, Hasanger C, Gryning S, Courtney M, Antoniou I, Mikkelsen T. Offshore wind profiling using light detection and ranging measurements. *Wind Energy* 2009, 12; 105-124.