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A Case Study of Laser Wind Sensor Performance Validation by Comparison to an Existing Gage

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Abstract-A case study concerning validation of wind speed measurements made by a laser wind sensor mounted on a 190 square foot floating platform in Muskegon Lake through comparison with measurements made by pre-existing cup anemometers mounted on a met tower on the shore line is presented. The comparison strategy is to examine the difference in measurements over time using the paired-t statistical method to identify intervals when the measurements were equivalent and to provide explanatory information for the intervals when the measurements were not equivalent. The data was partitioned into three sets: not windy (average wind speed measured by the cup anemometers ≤ 6.7m/s) windy but no enhanced turbulence (average wind speed measured by the cup anemometers > 6.7m/s), and windy with enhanced turbulence associated with storm periods. For the not windy data set, the difference in the average wind speeds was equal in absolute value to the precision of the gages and not statistically significant. Similar results were obtained for the windy with no enhanced turbulence data set and the average difference was not statistically significant ($\alpha=0.01$). The windy with enhanced turbulence data set showed significant differences between the buoy mounted laser wind sensor and the on-shore mast mounted cup anemometers. The sign of the average difference depended on the direction of the winds. Overall, validation evidence is obtained in the absence of enhanced turbulence. In addition, differences in wind speed during enhanced turbulence were isolated in time, studied and explained.

Keywords-Laser wind sensor; validation; offshore wind energy; paired-t statistical method.

1. Introduction

A Laser Wind Sensor (LWS) or lidar unit was used to gather wind data above Lake Michigan a significant distance from any land. This data could subsequently be used in computing the power and energy potential of the wind. Validation of the LWS is a prerequisite to the data gathering. Validation can be accomplished by comparison of the measurements made by the LWS unit with those of a trusted gage such as cup anemometers. As pointed out by Jamdade and Jamdade [1], speed is the most important wind characteristic. Thus, validation [2, 3] has to do with gathering evidence that the wind speed data collected by the LWS while positioned in Lake Michigan can be relied upon in computing power and energy potential.

For the validation study, the LWS is mounted on a 190 square-foot floating platform located on Muskegon Lake which is adjacent to Lake Michigan. Budgetary constraints required the use of an existing gage at approximately the same height as the lowest altitude measurement the LWS unit could make, 55m. The existing cup anemometers are mounted on a meteorological (met) tower situated nearby on the lakeshore. One effective comparison approach between measurements made by a gage on water and a gage on adjacent land at a lower height is described in [4]. The validation strategy is based on a hypothesis that each gage is measuring wind with the same speed characteristic. The numerical difference in wind speed measurements between the two gages at each observation time is computed to identify intervals when the wind speed was equivalent and to help provide explanatory information, including differences in wind direction, for the intervals when the measurements were not equivalent. The strategy is supported by the paired-t statistical method, with time being the common element.

The focus of wind project developers has expanded from land-based wind farms to include off-shore sites, with increasing interest toward constructing taller turbines in deeper waters. One critical, pre-requisite step in each project is an assessment of available winds. For decades, met masts with cup anemometers have been relied upon to record wind speed and wind vanes to record direction. However, the use of such met masts may not be feasible in deep water locations or to reach the hub height of taller turbines, particularly offshore.

While met masts are relatively easy to install on terrestrial sites, installation at offshore locations can be prohibitively difficult as well as publically and politically controversial. 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 in deeper water up to 30 m (e.g. FINO 1, Germany) [5]. Met towers in water in excess of 30m 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. Once a met tower is installed, it is difficult to change the heights at which the cup anemometers operate.

Musial and Ram [6] noted a need for tools that can measure wind speeds at multiple locations and determine wind shear profiles up to hub height. The authors also identified a need for stable buoy platforms to support the aforementioned assessment tools. To address this issue, a number of remote sensing technologies have emerged as potential alternatives to met tower mounted cup anemometers such as light detection and ranging (LiDAR), sound detection and ranging (SoDAR) and airborne synthetic aperture radar (SAR) sensors [7]. LiDAR and SoDAR operate similarly in that a signal (light or sound of a particular frequency) is emitted by the unit and the sensor captures and records the return signal. As the signal reflects off 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 [7].

The data collected by cup anemometers has long been trusted. However, there is comparatively little experience with the use of remote sensing technologies such as LWS units particularly in an offshore location. Thus, validation is a particularly critical step in the wind data assessment process when a remote sensing device is used offshore. There are a few reports of such validation activities regarding the comparison of LWS units with cup anemometers mounted on met masts in onshore and offshore settings. Several researchers reported coefficient of determination (R2) values of 0.99 for heights ranging from 60m to 116.5m and all wind speeds [8, 9]. Peña, Hasanger, Gryning, Courtney, Antoniou, and Mikkelsen [10] reported results of a validation experiment at the Horns Rev, Denmark. LWS measurements were compared to three met masts at 63 m and found a high level of agreement (R2 = 0.97-0.98). The measurement bias ranged from 0.12-0.15m/s for the LWS. Cup anemometer measurements from the FINO platform [11] also showed a high level of agreement with the corresponding lidar measurements (R2 = 0.99) and a bias of -0.15m/s to 0.08m/s at heights from 70m to more than 100m.

Thevenoud, Boquet, Thobois, and Davoust [12], Rogers et al.[13], Carbon Trust [14], and Howe and Thomsen [15] review other validation studies of wind speed measurement that show similar results.

- A LWS unit mounted on a floating platform with a second unit mounted on a fixed platform (R2 = 99.6%)

- A three month validation study at DTU's Høvsøre testing facility from mid-March 2013 to early May between a land based LWS unit and cup anemometers mounted on a met mast for heights 60m, 80m, and 100m resulting in R2 of 97% at 60m and 99% at 80m and 100m.

- A three month validation study from mid-March to mid-May 2013 in the Atlantic Ocean off Atlantic City, New Jersey between a floating platform based LWS unit and a shore-based WindCube resulting in R2 of 95% at 78m, 93m, and 113m.
- In October 2013, a comparison study between an LWS unit on a floating platform with an onshore WindCube 300m away at Tainan, Taiwan resulting in a R2 of 98% for 110m and 150m and a R2 of 99% for 200m.

Such validation studies lead to the conclusion that remote sensing of wind speeds using LWS units produces results indistinguishable from those of a traditional met tower mounted cup anemometers.

In addition, mounting an LWS unit on a floating platform introduces wave motion that could affect wind measurement and thus requires compensation. Musial and Ram [6] 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.

Pichugina, Banta, Brewer, Sandberg, and Hardesty [16] were among the first to document the use of shipboard LWS sensors with motion compensation. Their preliminary error propagation model 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” [p. 334]. Further, the Atlantic Ocean study discussed above concluded that “No significant sensitivity to pitch and roll motions was observed….this result is indicative of an efficient motion compensation performance of the floating LiDAR.”

In addition, the Juan de Fuca Strait study [15, 17, 18] was conducted to address compensation for dynamic motion with 6 degrees of freedom: translation in two directions and heave of the platform as well as roll, pitch, and yaw. One LWS unit was mounted on a floating platform in the Juan de Fuca Strait between the Olympic Peninsula and Vancouver Island. A comparison LWS unit was mounted on a small island 688 meters from the floating platform. Wind speed and direction were gathered for a one month period: 20 October to 20 November 2009 from range gates centered at 100, 150 and 200m. Results showed R2 = 99.5% for wind speed at each height between the two gages. Under the hypothesis that the two LWS units were observing wind with the same speed and direction characteristics, motion compensation is the only difference between the two measurement sites. Thus, validation evidence for the proprietary motion compensation algorithm was obtained.

All of the prior LWS validation studies referenced above used R2 as the primary measure of correspondence between two gages. The weakness of this approach is that periods of time when differences in measurements between the two gages existed are not identified and thus no explanatory information regarding such differences is provided. This case study uses the paired-t statistical method to generate a time series of differences in the wind speeds between two gages. The time series of differences is studied to identify time periods when the wind speed measured by the two gages are equivalent and time periods when the wind speeds are not equivalent. The former provides validation evidence for the LWS unit. The latter requires explanations as to the cause of the differences.

In addition, these studies use well-designed experiments with two gages located at the same site, or at least near each other, premised to consistently measure winds having the same speed and direction characteristics. This is an ideal experimental condition that might not always be possible due to the cost, permitting, and logistics of acquiring and co-locating two gages. This case study provides an approach when a pre-existing gage must be used and ideal experimental conditions cannot be met.

2. Methods

A LWS unit measures wind speed and direction every second as do the cup anemometers. Ten minute averages are computed from the one second observations. A ten minute average is considered valid if at least300 of the 600 observations are reported as valid by the device. This is the current industry defacto standard.

The paired-t method compares two samples in cases where each value in one sample has a natural partner in the other. In this case, each ten minute average computed from observations made by the LWS unit has a natural partner in the ten minute average computed from observations made by the cup anemometers for the same ten minute time interval, t.

The fundamental equation of the paired-t method generates a time series of differences as follows.

$$\text{difference}_t = \text{Comparison Gage}_t - \text{LWS Unit}_t \qquad (1)$$

A difference is valid if both of the ten minutes averages are valid. The application of equation 1 results in a time series of wind speed differences between the two gages.

Isolating time periods requires partitioning of the data, which was done using a windowing technique with a window size of one hour. If the average wind speed for the current point in time and the next 5 points in time was greater than a specified speed, then all six 10-minute averages in the window were assigned to the greater than specified speed 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 less than or equal to specified speed data set and the next 10-minute average in time sequence is considered.

The wind speed precision of the LWS unit and of the cup anemometers is 0.1m/s. Thus, an average difference in wind speed of less than 0.1m/s is considered operationally insignificant, a smaller value than can be measured. Thus, such differences are not of interest.

The coefficient of variation (Cv) is given by equation 2.

$$\text{Cv} = \frac{s}{\bar{x}} \qquad (2)$$

where s is the standard deviation of the differences and $\bar{x}$ is the average difference. The standard deviation corresponds to the random variation in the differences while the mean corresponds to real differences. Thus, the larger the values of Cv, the more the difference is due to random variation in wind speed as opposed to real differences in measured values. Another way to interpret Cv arises from realizing that it is the reciprocal of the signal-to-noise ratio. Thus, the larger the value of Cv, the more noise (random variation) and less signal (actual differences), which is the desired condition.

A WindSentinel buoy, including a LWS unit which was new when delivered in September 2011, was deployed in Muskegon Lake from 7 October through 3 November 2011. The LWS unit was located in Muskegon Lake at an altitude of 176m above sea level at coordinates: 43° 14’ 55” N; 86° 14’ 55” W. The LWS unit measures wind speed and direction in altitude intervals known as range gates. The LWS unit has a range gate centered at 55m above its mounting position on a buoy an additional 2.85m above the lake level. Thus, the range gate center height is 57.85m above the surface of Muskegon Lake.

The met mast was located on the Muskegon Lake shore in an open field at an altitude of 178m above sea level at coordinates: 43° 14’ 46” N; 86° 14' 41” W, a site 2.0m above lake level. Two anemometers at 48.5m above ground with one anemometer facing northwest and the other southeast are mounted on the met mast. Thus the anemometers are an effective 50.5m above Muskegon Lake. The cup anemometers are both model NRG 40 Sine. Each was calibrated in April 2011 in accordance with international standard ISO/IEC 17025:2005.

The maximum wind speed of the two anemometers was used. 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.

Fig. 1. Location of met mast and LWS unit in Muskegon Lake

Figure 1 illustrates the location of the two gages. The LWS unit and the anemometers were measuring wind speeds at slightly different heights and at locations 423.8m apart. The anemometers were on the edge of a large land mass and the LWS unit was over water. Thus, it is reasonable to hypothesize that some of the time each was measuring wind with different speed and direction characteristics.

3. Results and Discussion

To compute the time series of differences of the ten minutes average wind speed measurements between the LWS unit and the cup anemometers, Equation 1 is applied as shown in equation 3.

$$\text{difference}_t = \text{cup anemometer}_t - \text{LWS}_t \qquad (3)$$

Table 1 shows the number of observations by classification.

Table 1. Number of observations by classification.

Classification	Number of Observations

Total number of 10-min 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	409
Number of valid observations	3055
Percent of valid, non-missing observations	88.2%
Number of outliers	1
Number of observations used in study	3054
Number of observations used in study / Number of observation periods	79.3%

The LWS unit reported about 10% of the observations as missing. There was one extremely large wind speed value that could not be explained and was thus considered an outlier. Ten minute averages comprised of less than 300 one second observations, a total of 409, are considered invalid. Thus, 79.3% of the 10-minute averages were considered useable for analysis.

A graph of the 3054 pairs of 10-minute averages used in the study is shown in Figure 2. 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 cup anemometers (max48).

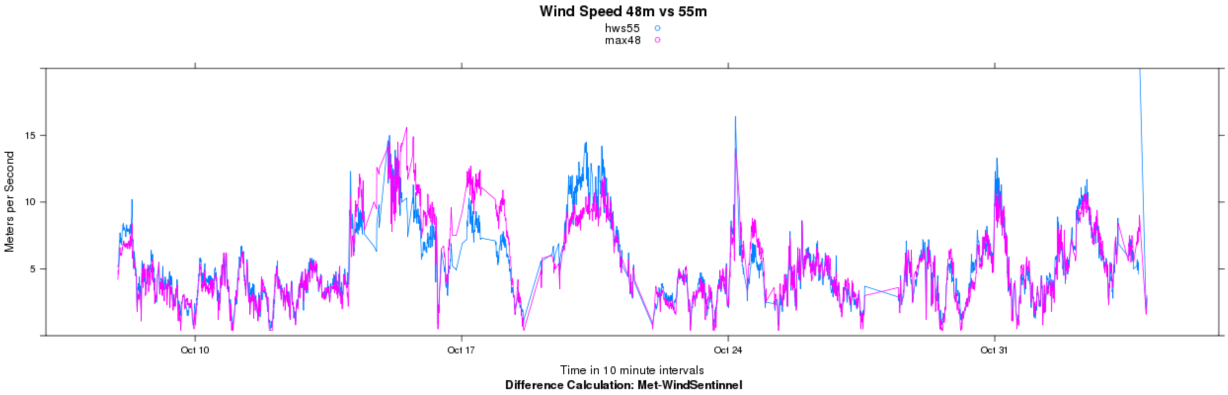

Fig. 2. Ten-minute average pairs from each gage.

A correlation graph is given in Figure 3. In this graph, differences at higher wind speeds are more easily seen. The correlation coefficient (R) is 91.96%. Thus R2 is 84.57%. The red line represents perfect (100%) correlation and the black line represents the estimated correlation.

As seen in Figure 3, the correlation between the wind speeds measured by the two gages lessens dramatically at about 6.7m/s (15mph). Thus, the dataset was partitioned into two subsets based on the wind speed measured by the anemometers on the met mast: ≤ 6.7m/s and > 6.7m/s. Table 2 shows the number of observations in each data set resulting from this partitioning.

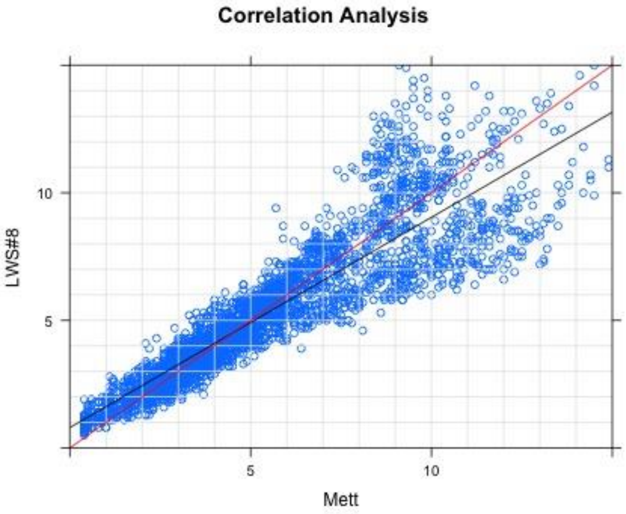

Fig. 3. Ten-minute average pairs correlation

Table 3 summarizes the results of the paired-t analysis. The hypothesis: the magnitude of the mean difference is 0.1 (the precision of the gage) is tested. The alternative hypothesis is that the magnitude of the mean difference is not 0.1. This is a two-sided test.

Table 2. Number of observations in dataset.

Classification	**Number of Observations**
Number of observations used in study	3054
Number of observations ≤ 6.7m/s	2124
Number of observations > 6. m/s	931
% of observations ≤ 6.7m/s	69.5%
% of observations > 6.7m/s	30.5%

The magnitude of the mean difference is 0.1m/s. The confidence interval, which is a set of plausible values for the true mean, does contain -0.1 meaning that a conclusion of an operationally significant difference between the two gages is not supported by the data. In other words, since the range of operationally insignificant values is [-0.1, 0.1] and the confidence interval overlaps with this range, strong statements cannot be made about the difference being greater in magnitude than 0.1.

Furthermore, the magnitude of the coefficient of variation is much greater than 1 indicating that differences in the observations made by the two data sets can be viewed as random variation. Thus, validation evidence for the LWS is obtained for wind speeds less than or equal to 6.7m/s.

Table 3. Paired-t analysis for the ≤ 6.7m/s data set.

Data Set	Mean Difference (m/s)	Standard Deviation (m/s)	Coefficient of Variation	R2	Number of Differences (n)	99% Confidence Interval	
						Lower Bound	Upper Bound
≤ 6.7m/s	-0.10	0.58	-5.7	83.4%	2124	-0.13	-0.069

Table 4. Paired-t analysis for the > 6.7m/s no enhanced turbulence data set.

Data Set	Mean Difference (m/s)	Standard Deviation (m/s)	Coefficient of Variation	R2	Number of Differences (n)	99% Confidence Interval	
						Lower Bound	Upper Bound
> 6.7 m/s no enhanced turbulence	-0.061	1.2	-20	62.4%	416	-0.22	0.096

In addition, the sign of the difference is negative indicating that the cup anemometer reading is slower. This is consistent with the idea that wind speed over a rougher surface (land) should be less. Furthermore, some difference in mean wind speed is expected due to the difference in heights above Muskegon Lake of the two gages.

The analysis of the > 6.7m/s dataset was performed in two parts: observations that were windy but not during periods of enhanced turbulence such as that due to storms, and observations during three periods of enhanced turbulence (storms identified by generally available weather information).

Table 4 shows the paired t-analysis for the > 6.7m/s no enhanced turbulence dataset. The magnitude of the mean difference is than less 0.1m/s. This difference is not statistically significant (α=0.01) as the 99% confidence interval for the true mean difference contains -0.1. Again, the coefficient of variation is much greater than 1 indicating that the mean difference is due to random variation. Thus, validation evidence is obtained for wind speeds greater than 6.7m/s and no enhanced turbulence. The R2 value of 62.4% is likely due to a few large differences seen at high wind speeds (Figure 3).

Table 5. Enhanced turbulence period time blocks.

Day Start	**Time Start (UTC)**	**Day End**	**Time End (UTC)**	**Comments**
10/14	1:30	10/16	9:10	Period 1
10/16	16:00	10/18	7:00	Period 2
10/19	16:30	10/21	3:40	Period 3

Table 5 shows the time periods during which enhanced turbulence (storms) was observed.

Table 6. Paired-t analysis for the > 6.7m/s enhanced turbulence data set.

Data Set	Mean Difference (m/s)	Standard Deviation (m/s)	Coefficient of Variation	R^2	Number of Differences (n)	99% Confidence Interval	
						Lower Bound	Upper Bound
> 6.7m/s Period 1	1.2	1.6	1.34	55%	207	0.92	1.5
> 6.7m/s Period 2	2.5	0.88	0.27	87%	126	2.4	2.7
> 6.7m/s Period 3	-1.5	1.4	-0.98	39%	181	-1.7	-1.2

Table 6 shows the paired t-analysis for the > 6.7m/s enhanced turbulence dataset by period.

Mean differences in measurements between the buoy-mounted LWS unit and the mast-mounted cup anemometers during periods of enhanced turbulence are both operationally significant, of the order of 1m/s to 3m/s, and statistically significant (α=0.01). The results for all three such periods are consistent: a significantly lower level of agreement between the two gages. The coefficient of variation is much smaller than in other time periods, indicating actual differences as opposed to variation only. Comparison of these results with those from other studies in not possible as most LWS unit validation studies exclude observations made under enhanced turbulence conditions [8, 10].

1. Some insight into the differences is in order as follows. The sign of the mean difference is consistent with the direction of the wind during the enhanced turbulence periods. The wind direction was as follows: Period 1 from the northwest, over water; Period 2 from the west, over water; and Period 3 from the northeast, over land. Thus, wind direction from over water indicates higher wind speed on land and vice versa.
2. The surface roughness over land (met mast) is likely greater than the surface roughness over water (LWS). Thus some difference in wind speed is expected, which may be more pronounced during enhanced turbulence.

4. Conclusion

The coefficient of determination R2 has been commonly used in validation studies as the primary metric of equivalency between two gages. However, this metric cannot identify periods of time when differences in the speed of winds measured by two gages occur. An approach for examining the time series of differences in wind speeds based on the paired-t statistical method has been shown to be effective in identifying and explaining time periods when significant differences in wind speeds were measured.

This result provides the foundation for validating a LWS unit on a floating platform in Muskegon Lake by comparison to existing cup anemometers installed on a met tower on the shoreline which served as a calibrated and trusted gage. The data was partitioned into three sets: not windy (average wind speed measured by the cup anemometers ≤ 6.7m/s), windy but no enhanced turbulence (average wind speed measured by the cup anemometers > 6.7m/s), and windy with enhanced turbulence (again, average wind speed measured by the cup anemometers > 6.7m/s).

Validation evidence for the wind speed measures made by the LWS unit by comparison to the cup anemometer wind speed measurements were obtained as follows. The paired-t analysis for the not windy data set showed a difference in the average wind speeds of -0.10m/s, equal in absolute value to the smallest value either gage will measure. The negative sign indicates slower wind speed over land as well as at a lower height, which is expected. Furthermore, the magnitude of the coefficient of variation is much greater than 1 indicating that differences in the observations made by the two data sets can be viewed as random variation. Similar results were obtained for the windy with no enhanced turbulence data set. In addition, the average difference was not statistically significant (α=0.01). Thus, evidence that the LWS unit could be trusted to provide reliable wind speed measurements was obtained.

The windy with enhanced turbulence data set showed significant differences between the two gages. The sign of the average difference depends on the direction of the winds. There is greater surface roughness over land than over water which may be have an increased impact during periods of enhanced turbulence. Thus, there is a plausible foundation for the observed difference in average wind speed during enhanced turbulence.

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