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Laser Wind Sensor Performance Validation with an Existing Gage

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Abstract

A new approach to laser wind sensor measurement validation is described and demonstrated. The new approach relies on the paired-t statistical method to generate a time series of differences between two sets of measurements. This series of differences is studied to help identify and explain time intervals of operationally significant differences, which is not possible with the traditional approach of relying on the squared coefficient of variation as the primary metric. The new approach includes estimating a confidence interval for the mean difference and establishing a level of meaningful difference for the mean difference, and partitioning the data set based on wind speed.

To demonstrate the utility of the new approach, measurements made by a laser wind sensor mounted on a floating buoy are compared first with those made by a second laser wind sensor mounted on a nearby small island for which the co-efficient of variation is high (> 99%). It was found that time intervals when high differences in wind speed occurred corresponded to high differences in wind direction supporting a hypothesis that the two laser wind sensor units are not always observing the same wind resource. Furthermore, the average difference for the 100m range gate is positive, statistically signficant (α=0.01) and slightly larger than the precision of the gages, 0.1m/s. One possible cause of this difference is that the surface roughness over land is slowing the wind at 100m slightly.

A second comparison was made with previously existing cup anemometers mounted on a metrological mast located on-shore. The cup anemometers are about 8m lower than the center of the lowest range gate on the laser wind sensor. The data was partitioned into three sets: not windy (average wind speed at the cup anemometers **≤** 6.7m/s) windy but no enhanced turbulence (average wind speed at the cup anemometers > 6.7m/s), and windy with enhanced turbulence. Periods of enhanced turbulence are associated with the passage of a cold frontal boundary.

The paired-t analysis for the not windy data set showed a difference in the average wind speeds of -0.096m/s, less in absolute value than the precision of the gages. The negative sign indicates slower wind speed over land as well as at a lower height, which is expected. 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).

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 in the periods of enhanced turbulence. Mean turbulent kinetic energy was measured to be greater when air flow into Muskegon Lake was predominantly from over land versus when air flow was predominantly from Lake Michigan. The higher mean turbulent kinetic energy for flow originating over land would likely be due to greater surface roughness experienced by the overland flow.

Overall, the value of the new approach in obtaining validation evidence has been demonstrated. In this case, validation evidence is obtained in periods of no enhanced turbulence. Differences in wind speed during periods of enhanced turbulence are isolated in time, studied and are correlated in time with differences in wind direction.

1.0 Introduction

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 wind resources. For decades, meteorological ("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.

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 30m (e.g. FINO 1, Germany) (Wissemann, 2008). 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.

The wind resources at hub height are often approximated through the use of mathematical and statistical models (Bagiorgas et al. 2012; Veigas and Iglesias 2012). Following Lu et al. (2002), the estimation of the variation of wind speed with height is obtained using a power law relationship with which the wind speed (V) at hub height (Z) is estimated from the wind speed (V_0) measured at some reference height (Z_0), usually between 3m and 10m.

$$\frac{V}{V_0} = \left(\frac{Z}{Z_0}\right)^{a} \qquad (1)$$

Lu et al. (2002) note that the exponent, α, varies with height, time of day, season, nature of the terrain, wind speeds, and temperature. While a value of one-seventh is typically used, the value can be estimated for a given flow condition if the wind speed is known at two heights. The value obtained from these two measurements can then be applied to estimate the wind speed at a third level, in this case the hub height.

Alternatively, 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 (Musial and Ram 2010).

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 (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 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 (Hasanger et al. 2008).

The data collected by cup anemometers has long been trusted. However, there is comparatively little experience with the use of remote sensing technologies particularly in an offshore location. Thus, validation is a particularly critical step in the wind resource data collection process when such a device is used offshore. Validation has to do with gathering evidence that the collected data, such as wind speed and direction at various heights above the water surface, can be relied upon in computing power and energy potential as well as for decision making regard project economic viability (Sargent, 2012). One common form of validation evidence is comparison to a trusted gage such as a previously calibrated and tested cup anemometer posted on a met tower nearby or a second remote sensing unit operated in parallel.

There are several reports of such validation activities regarding the comparison of laser wind sensor units (LWS) with cup anemometers mounded on met masts in onshore and offshore settings. Danish researchers reported R^2 values of 0.99 for heights ranging from 60m to 116.5m and all wind speeds (Kindler et al. 2009). Hasanger et al. (2011) reported results of a validation experiment at the Horns Rev, Denmark. LWS measurements were compared to three met masts at 63m and found a high level of agreement (R^2 = 0.97-0.98). The measurement bias ranged from 0.12-0.15m/s. LWS. Cup anemometer measurements from the FINO platform (Westerhellweg et al. 2010) 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 70m to more than 100m. These and other studies lead to the conclusion that remote sensing of wind speeds using LWS produces results indistinguishable from those of a traditional met tower.

Mounting an LWS unit on a floating platform introduces wave motion that could affect wind measurement and thus requires compensation. A 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 (Musial and Ram, 2010).

Pichugina et al. (2012) 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 0.10m/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" (Pichugina et al. 2012, p. 334).

Jaynes (2011) as well as AXYS Technologies (2010) describe a study that addresses this issue: compensation for dynamic motion with 6 degrees of freedom for a LWS mounted on a floating platform including translation in two directions and heave of the platform as well as roll, pitch, and yaw of the LWS. The data was gathered from two identical LWS units. One unit was mounted on a small island 688 meters from the other unit which was mounted on a floating platform in the Juan de Fuca Strait between the Olympic Peninsula and Vancouver Island. Data was gathered for a one month period:

October 20, 2009 to November 20, 2009. The data included wind speed and direction at 100, 150 and 200 meters; wave height and direction; air and water temperature; and barometric pressure. Results showed a 99% coefficient of variation (R^2) for wind speed at each height between the two gages. Since motion compensation is the only difference between the two measurement sites, validation evidence for the motion compensation algorithm is obtained.

All of the prior LWS validation studies referenced above use R^2 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.

Furthermore, all of the studies report well-designed experiments with two gages premised to measure the same wind. This is an ideal that might not always be possible due to the cost, permitting, and logistics of acquiring and co-locating two gages, particularly if one is a met tower with cup anemometers. Of particular interest is the situation where one of the gages is an LWS mounted on a floating platform acquired to measure off-shore wind a significant distance from any land and where cost constraints require comparison to an existing gage located on the shoreline. Given the view of validation as the process of building confidence that the data gathered by the LWS can be used for power estimation and other decision making, using R^2 as the primary metric seems insufficient for this case.

This paper describes an approach to validation for the situation where an LWS mounted on a floating platform is compared to existing cup anemometers mounted on a land-based met tower. The strategy is to examine the difference in measurements between the two gages over time to identify intervals when the measurements were equivalent and to provide explanatory information for the intervals when the measurements were not equivalent. The strategy is implemented using the paired-t statistical method, with time being the common element. This approach is illustrated for an LWS on a floating platform acquired for collecting wind resource information in Lake Michigan with measurement comparisons made to existing cup anemometers mounted on a met tower located on the shoreline of Muskegon Lake.

First the approach is introduced by extending the study reported by Jaynes (2011) and AXYS Technologies (2010) discussed above to show its value even between two gages premised to measure equivalent wind with a high R^2 reported.

2.0 Approach Introduction and Extension of the Juan de Fuca Strait Study

Each of the two LWS units in this study observed wind speed and direction at 100m, 150m, and 200m each second. Ten minute averages were computed. Only the 10-minute averages consisting of at least 300 valid one-second observations out of a possible 600 were included in the analysis. This is the current industry defacto standard for aggregating one-second observations. The LWS unit referred to as the Land Station is on a small island. The other referred to as the Wind Sentinel is mounted on the flowing platform or buoy.

The fundamental equation of the paired-t statistical method generates the time series of differences in the 10-minutes averages observed by the LWS units for each of the three heights:

$$\text{difference}_t = \text{Wind Sentinel}_t - \text{Land Station}_t \quad (2)$$

Given the definition of a valid 10-minute average, a valid difference is one for which both 10-minute averages are valid. Applying this definition resulted in 3022 differences at each of the three heights out of a possible 4464, 67.7%. The average difference is Student's t-distributed with degrees of freedom of one less than the number of valid differences.

An average difference of less than 0.1m/s, the precision of each gage, is considered operationally insignificant for our purposes. This value is the smallest non-zero measurement made by either a LWS or a cup anemometer. In other words, the hypothesis is the difference between the mean wind speed measured one gage and the mean wind speed measured by a second gage is equal to the precision of a gage.

The coefficient of variation (c) is also of interest:

$$c = \frac{s}{\bar{x}} \quad (3)$$

where s is the standard deviation of the differences and $\bar{x}$ is the average difference.

With respect to the difference series, the larger the value of c the better, which results when the standard deviation is larger than the mean. The standard deviation corresponds to the random variation in the differences while the mean corresponds to real differences. Thus, the larger the values of c, the more the difference is due to random variation in wind speed as opposed to real differences in measured values.

Another way to interpret c arises from realizing that it is the reciprocal of the signal-to-noise ratio. Thus, the larger the value of c, the more noise (random variation) and less signal (actual differences), which is the desired condition.

First consider a plot of the differences shown in Figure 1. Note that wsd100 represents the wind speed difference between the instruments for the 100 meter range gate, wsd150 represents the wind speed difference for 150 meter range gate, and wsd200 represents the wind speed difference for the 200 meter range gate.

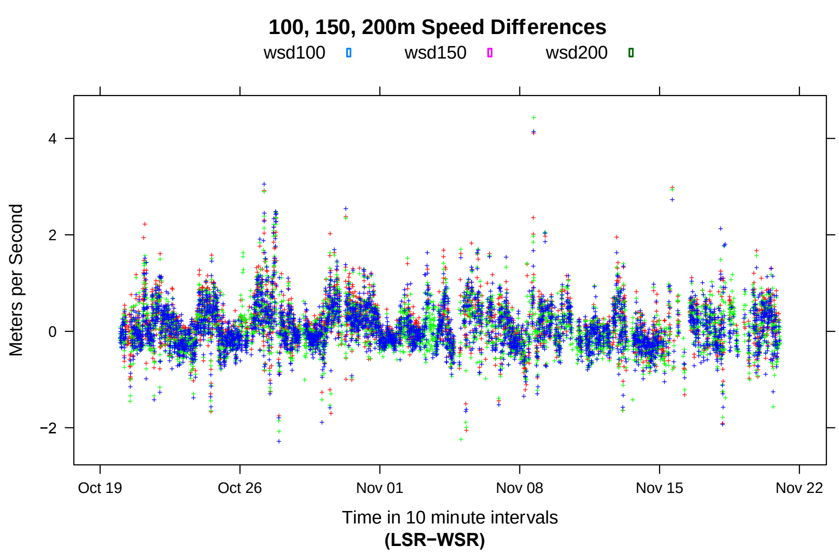

Figure 1: Speed Differences for Each Range Gate

Note despite the R^2 values of at least 99% at each range gate height that differences often exceeding 2m/s and occasionally 4m/s are observed. An explanation for these differences must be sought. In this regard, consider the plot of wind direction difference, expressed in degrees with north equal zero, shown in Figure 2.

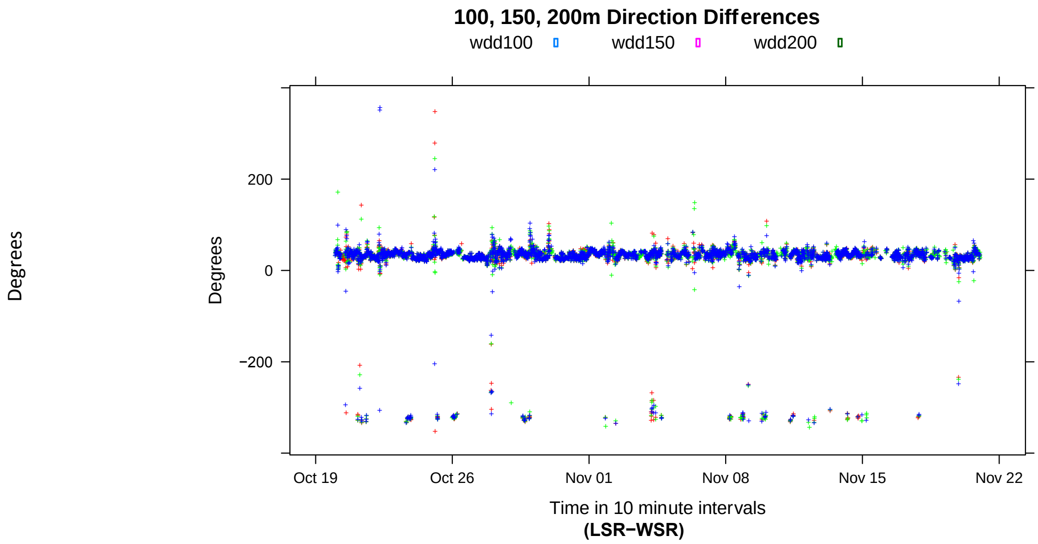

Figure 2: Direction Differences for Each Range Gate

The information shown in Figure 2 indicates that direction differences are of the same magnitude for each height and that large differences for speed and direction occur at the same points in time. Thus, it appears that differences in speed are correlated to differences in wind direction. This is consistent with the hypothesis that the wind at the two LWS units, which are 688 meters apart, is not always the same or in other words the two LWS are not always observing the same wind. Note that the differences are in isolated time periods. Thus, it is unlikely that these differences are due to causes such as instrument calibration error or poor buoy motion correction.

A statistical summary of the wind speed difference series for each range gate is shown in Table 1.

Table 1: Statistical Summary of Wind Speed Difference Series

Range Gate Height (m)	Mean Difference (m/s)	Standard Deviation (m/s)	Coefficient of variation	Number of differences (n)	99% Confidence Interval	
					Lower Bound	Upper Bound
100	0.13	0.48	3.7	3022	0.11	0.15
150	0.076	0.48	6.4	3022	0.053	0.099
200	0.074	0.48	6.5	3022	0.052	0.096

The results for the 150m and 200m range gates are virtually identical. The mean difference, as well as the 99% confidence interval for the mean difference, are less than 0.1m/s the smallest operationally significant value. The coefficient of variation is much larger than 1, indicating that difference series is comprised mostly of random variation.

Conversely for the 100m range gate, the mean difference, as well as the 99% confidence interval, are greater than 0.1m/s. The standard deviation is the same as for the other two range gates and thus the coefficient of variation is smaller.

The graphs shown in Figures 1 and 2 as well as the summary data shown in Table 1 provide the basis for insights into differences between the wind measurements made by the two gages. Such differences are not apparent when the time series of differences is not examined that is when R^2 is the primary measure of comparison. Points in time when high differences in wind speed occur correspond to high differences in wind direction suggesting that the two LWS units are not always observing the same wind resource. The average difference for the 150m and 200m ranges gates is less than the smallest operationally significant difference of 0.1m/s but the average difference for the 100m range gate is positive and slightly larger than 0.1m/s. One possible cause of this difference is that the surface roughness over land is slowing the wind at 100m slightly, while having a limited effect at 150m and 200m.

Thus, the benefits of examining the difference series of wind speeds between two gages is shown even for the case where the coefficient of determination between the two wind speed measurements is high.

3.0 Comparison of Floating Platform Mounted LWS and Met Mast Measurements

A WindSentinel buoy, including a LWS unit, was acquired in September 2011 and deployed in Muskegon Lake from 7 October 2011 through 3 November 2011. (This LWS unit is not one of the two LWS units used in the Juan de Fuca Strait Study.) The buoy was positioned 423.8m (calculated at http://jan.ucc.nau.edu/~cvm/latlongdist.html) offshore from a 50m onshore met mast at the east end of the lake. The location of each sensor was as follows:

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 LWS unit has a range gate centered at 55m, but is mounted on the buoy an additional 2.85m above the lake level. The corrected LWS lens height is 57.85m above the surface of Muskegon Lake. The onshore met mast contains two anemometers at 48.5m above ground with one anemometer facing northwest and the other southeast. 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. The met mast site is 2.0m above the lake level. This puts the anemometers an effective 50.5m above Muskegon Lake.

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 a different wind resource.

Figure 3: Location of Met Mast and LWS unit in Muskegon Lake

3.1 Wind Observations and Dataset Partitioning

One-second (1 Hz) wind observations were collected. Ten-minute average wind speeds were computed for non-overlapping periods from the one-second observations. As in the Juan de Fuca Strait Study, only 10-minute averages consisting of at least 300 one-second observations were considered valid.
The time series of differences is generated using Equation 4.

$$\text{difference}_t = \text{met mast}_t - \text{LWS}_t. \qquad (4)$$

Recall that met mast_t is the maximum of the wind speed averages for the two anemometers. A valid difference is one for which both the met mast and LWS averages are valid. A missing observation is one for which either the met mast or the LWS average was not recorded.

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. There was one extremely large wind speed value that could not be explained and was thus considered an outlier. Thus, 83.0% 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 tower anemometers (max48).

A correlation graph is given in Figure 5. In this graph, differences at higher wind speeds are more easily seen. The correlation coefficient is 90.15%. The red line represents perfect (100%) correlation and the black points represent the estimated correlation.

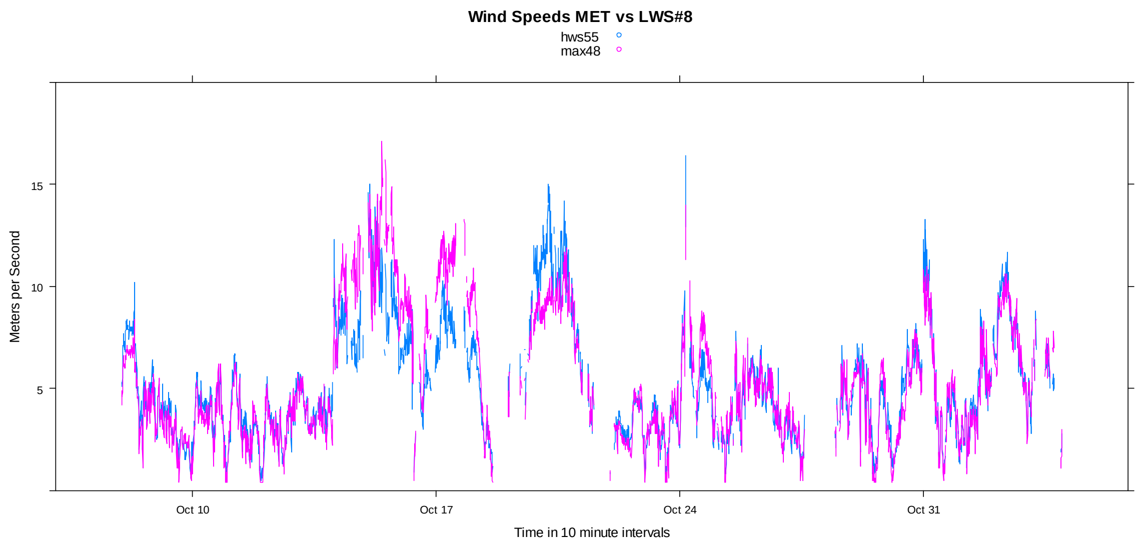

Figure 4: 10-Minute Average Pairs from Each Gage

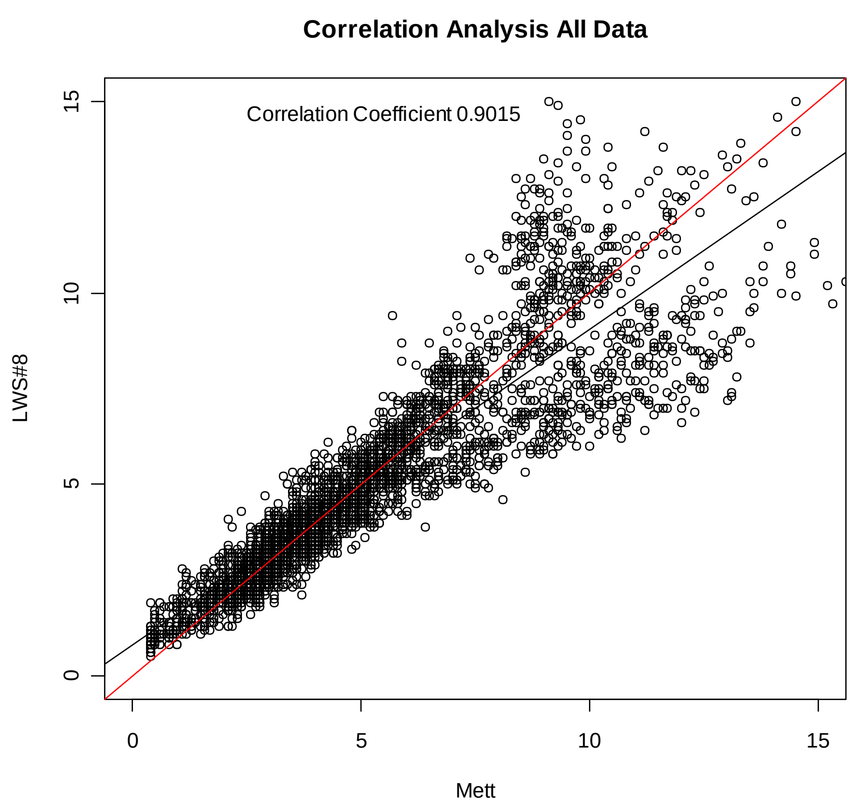

Figure 5: 10-Minute Average Pairs Correlation Plot

As seen in Figure 5, the correlation between the wind speeds measured by the two gages lessens dramatically at about 6.7m/s or 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. 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 > 6.7m/s, then all six 10-minute averages in the window were assigned to the > 6.7m/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 ≤ 6.7m/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 Dataset

Classification	**Number of Observations**
Number of observations used in study	3193
Number of observations ≤ 6.7m/s	2149
Number of observations > 6. m/s	1044
% of observations ≤ 6.7m/s	67.3%
% of observations > 6.7m/s	32.7%

3.2 Analysis of the <6.7m/s Dataset

Table 4 summarizes the results of the paired-t analysis for the hypothesis that the mean difference is zero with the alternative hypothesis that the mean difference is not zero.

Table 4: Paired-t Analysis for the ≤ 6.7m/s 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	-0.096	0.58	-6.1	91.2%	2149	-0.13	-0.064

The magnitude of the mean difference is slightly less than 0.1m/s. Thus, this difference is not operationally significant, even though it is statistically significant (α=0.01) as the 99% confidence interval for the mean difference does not contain zero. 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.

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, as well as correlation less than in the Juan de Fuca Strait study, is expected due to the difference in heights above Muskegon Lake of the two gages.

3.3 Analysis of the > 6.7m/s dataset (no enhanced turbulence)

The analysis of the > 6.7m/s dataset was performed in two parts: observations that were windy but not during periods of enhanced turbulence, and observations during three periods of enhanced turbulence. Table 5 shows the paired t-analysis for the > 6.7m/s no enhanced turbulence dataset.

Table 5: 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	R^2	Number of Differences (n)	99% Confidence Interval	
						Lower Bound	Upper Bound
> 6.7 m/s no enhanced turbulence	-0.028	1.1	-39	65%	416	-0.17	0.11

The magnitude of the mean difference is less 0.1m/s. This difference is neither operationally significant nor statistically significant (α=0.01) as the 99% confidence interval for the true mean difference contains zero. 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 correlation coefficient of 65% is due to a few large differences seen at high wind speeds (Figure 5) as would be expected.

3.4 Analysis of the > 6.7 m/s dataset (enhanced turbulence periods)

Table 6 shows the time periods during which enhanced turbulence was observed.

Table 6: 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 7 shows the paired t-analysis for the > 6.7m/s enhanced turbulence dataset by period.

Table 7: 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	R^2	Number of Differences (n)	99% Confidence Interval	
						Lower Bound	Upper Bound
> 6.7m/s Period 1	1.8	1.9	1.1	64%	262	1.5	2.1
> 6.7m/s Period 2	2.8	0.88	0.32	88%	174	2.6	3.0
> 6.7m/s Period 3	-1.6	1.5	0.98	61%	191	-1.8	-1.3

Mean differences in measurements between buoy-mounted LWS unit and the mast-mounted cup anemometers during periods of enhanced turbulence are both operationally significant, of the order of 2m/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.

Some insight into the differences is in order as follows.

1. 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 (Peña et al. 2009, Kindler et al. 2009).
2. The sign of the mean difference is consistent with the direction of the wind during the enhanced turbulence periods. The wind direction is 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.
3. The surface roughness over land (met mast) is greater than the surface roughness over water (LWS). Thus some difference in wind speed is expected, which may be more pronounced during enhanced turbulence.

An analysis of the one second observations provides support for items 2 and 3. Mean Turbulent Kinetic Energy (TKE) was measured to be greater when air flow into Muskegon Lake was predominantly from over land versus when air flow was predominantly from Lake Michigan. The higher mean TKE for flow originating over land would likely be due to greater surface roughness experienced by the overland flow. During the period on Oct 19th with wind direction from Land toward Sea, the TKE fluctuations are much higher than for an equivalent magnitude wind with direction from Sea to Land (Oct 16th). During the Land to Sea period, the spikes in the TKE are on the order of 5 times that of the Sea to Land period.

Thus, the observed difference in wind speed between the two gages during periods of enhanced turbulence seems reasonable.

4.0 Summary

A new approach to the validation of an LWS unit mounted on a floating platform with existing cup anemometers mounted on a land-based met tower nearby is described and applied. The two gages are not at the same height.

The new approach involves generating the time-series of differences between the 10-minute averages of one-second observations made by each gage. Using the statistical paired-t method, the coefficient of variation, and related graphs, the new approach improves upon the methods used in previous studies that relied on the coefficient of determination (R^2) as the primary measure of comparison. The new approach focuses on studying the time-series of differences to identify times of agreement between the instruments as well as to isolate and explain time periods when the gages appear to be measuring different wind.

To show the value of the new approach, a previously reported validation study with high R^2 = 99% is extended. The study compared two LWS units: one on a small island and the other mounted on a floating platform. The high R^2 value provided validation evidence for the motion compensation algorithm associated with the LWS unit on the floating platform. The additional value of the new approach was shown by identifying that large absolute values in the time-series of wind speed differences occurred in the same time periods as large differences in wind direction, supporting the hypothesis that during these time period the gages were observing different wind.

The validation study of a different LWS unit mounted on a floating platform in Muskegon Lake with cup anemometers mounted on a met tower on the lake shore nearby was conducted using the new method. The data was partitioned into three sets: not windy (average wind speed at the cup anemometers **≤** 6.7m/s), windy but no enhanced turbulence (average wind speed at the cup anemometers > 6.7m/s), and windy with enhanced turbulence (again, average wind speed at the cup anemometers > 6.7m/s).

The paired-t analysis for the not windy data set showed a difference in the average wind speeds of -0.096m/s, less in absolute value than the 0.1m/s 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 (6.1) 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 unit is obtained.

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).

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. Mean TKE was measured to be greater when flow was predominantly from over land versus when flow was predominantly from Lake Michigan. The higher mean TKE for flow originating over land would likely be due to greater surface roughness experienced by the overland flow. Thus, there is a plausible foundation for the observed difference in average wind speed during enhanced turbulence.

Overall, validation evidence is obtained in the absence of enhanced turbulence. In addition, differences in wind speed during enhanced turbulence can be isolated in time, studied and explained.

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