

# THE PERFORMANCE VALIDATION AND OPERATION OF NEARSHORE WIND MEASUREMENTS USING THE FLOATING LIDAR

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Preliminary assessments of the floating LiDAR have shown the technology to have significant potential for wind field measurements in the wind energy industry. To calibrate the motion compensation and validate the performance of the floating LiDAR, flume test and harbor test were conducted in a super wave tank (300m\*5.0m\*5.2m) at Tainan Hydraulics Laboratory (THL) and Hsing-Da Harbor, respectively. The comparisons of wind speed and direction profiles between the floating LiDAR and land-based LiDAR WINDCUBE v2, and regression analysis show the motion compensation is calibrated well. Besides, the wind data of three typhoon events were measured to investigate the wind characteristics, such as turbulence intensity and wind direction.

*Keywords: floating LiDAR, land-based LiDAR, wind speed, wind direction, regression analysis*

## INTRODUCTION

Accurate and reliable measurements of wind speed profiles through the lowest several hundred meters of the atmosphere are an important but difficult challenge for wind resource assessment. Traditionally, the anemometer and wind vane were installed in the met mast to get the wind resource data. However, the cost is too high comparing with the remote sensing techniques such as radar, sodar, and LiDAR(Light Detection And Ranging). Although the setup of met mast can be an option, the mobility is its weakness and limitation. Here, we describe a motion compensating, scanning Doppler LiDAR-based wind measurement system that is capable of producing reliable vertical profiles of marine wind speed and direction from shipboard at high resolution.

Studies on land using NOAA's High-Resolution Doppler LiDAR (HRDL) have demonstrated the ability of this instrument to reveal the structure and evolution of boundary layer processes up to several hundred meters above the ground at fine vertical, horizontal, and temporal resolutions. To demonstrate the ability of shipborne Doppler LiDAR to provide high-quality measurements in the marine boundary layer (MBL), it shows examples of analysis obtained from HRDL measurements during the New England Air Quality Study (NEAQS) in the summer of 2004.

In 2008, Technical University of Denmark (DTU) has established the Test Station for Large Wind Turbines at Hovsore in western Jutland, Denmark. Comparisons of wind profiles and turbulence intensity were done using two LiDAR systems, including English company QinetiQ ZephIR and French company Leosphere's WINDCUBE, respectively.

In 2013, a LiDAR measurement campaign was designed to assess the uncertainty of LiDAR in complex terrain. The experiment was conducted at a complex mountain range in southwest Norway consisting of elevations between 250 and 560 meters with terrain slopes up to 60 degrees. Three different LiDAR systems including WINCUBE, ZephIR and Galion LiDAR were tested against measurement masts in highly complex terrain over 4 months.

Until very recently, wind LiDAR systems required a fixed platform for operation, which made their offshore deployment cost nearly the same as an offshore met tower since most of the cost is for the foundation and platform, not the tower. In the last few years, at least four LiDAR systems-the SeaZephIR<sup>TM</sup>, WindSentinel<sup>TM</sup>, WaveScan<sup>TM</sup>, and FLiDAR<sup>TM</sup>-have come to market mounted on specially designed floating platforms. Two basic design philosophies for these platforms are emerging. The SeaZephIR limits the motion of the platform with a vertical spar buoy and a tension leg anchoring system, keeping pitch/roll very close to neutral. This strategy intends to negate the need for a motion compensation algorithm. The other three are based on a barge hull buoy with catenary anchor lines. The barge buoy data are processed with a digital algorithm to reduce the effects of platform motion. This motion-compensation algorithm subtracts the buoy motion effect from the wind vector data. Processing can occur internally in the unit or in a separate algorithm after data is downloaded. The Wavescan, the WindSentinel and the FLiDAR systems use some variation of this design. These units include renewable power systems designed for long term (6-12 months) deployments, and they can store the data or transmit via satellite or cell network, in bursts at regular intervals. They can be deployed adjacent to a turbine or far away from the wind farm, depending on the application, and can be easily re-deployed by a buoy tender or similar working vessel, providing the ability to easily and quickly collect data to blade tip height at almost any location. Several recent studies in the US and EU examined the accuracy of these systems, and some validation field tests are currently underway.

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In 2010, buoy manufacturer AXYS Technologies field tested the WindSentinel buoy at Race Rocks, British Columbia. 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. In 2011, a WindSentinel buoy of Grand Valley State University (GVSU) was deployed in Lake Michigan to validate with the met masts mounted cup anemometers. Also, the results show the effective motion compensation.

The WindSentinel™ buoy measures wind at different elevations using LiDAR technology. Various met and oceanographic sensors are installed on the WindSentinel™; the measured data is stored and transmitted over various telemetries. The primary function of the WindSentinel™ is to collect data for the purpose of wind farm assessment. The WindSentinel™ uses the AXYS Technologies Inc. (AXYS) WatchMan500™ (WM500) controller to control data collection, telemetry and storage. Along with the WM500, the DMS (Data Management System) software suite provides tools to retrieve, store and view data. AXYS can integrate a wide range of sensors onto a buoy system in order to meet the data needs of the offshore renewable energy sector. Sensor suites can be customized to supply data sets commonly used in this industry including: (1) wind speed, direction and gust (2) wave period and direction (3) significant and maximum wave height (4) current speed and direction (5) air and water temperature (6) relative humidity (7) atmospheric pressure (8) pH (9) dissolved oxygen (10) conductivity. The portable land-based WINDCUBE v2 LiDAR remote sensor collects measurements at heights up to 200 meters, mapping the vertical wind component, wind speed and direction, turbulence and wind shear. The WINDCUBE v2 is an active remote sensor based on LiDAR technique. Wind LiDAR relies on the measurement of Doppler shifted laser light backscattered by particles in the atmosphere (dust, aerosols). LiDAR is the only remote sensor technology to measure the absolute speed of the wind, making it the best choice to meet the industry's high accuracy requirements.

## PERFORMANCE VALIDATION

### Flume test

The flume tests were conducted in a super wave tank (300m\*5.0m\*5.2m) at Tainan Hydraulics Laboratory (THL), National Cheng Kung University (NCKU), Tainan, Taiwan on May 24, 2013. The wave period and height were 9 sec and 0.55 meter, respectively. To avoid the lateral motion of the buoy, four ropes were tied appropriately at the sidewall. For the convenience of discussion, the AXYS WindSentinel™ was labeled as laser wind sensor (LWS) later. Also, a land-based LiDAR called WINDCUBE v2 setup near the buoy was used to validate with the LWS, and the impact of nearby building to wind measurement can be neglected due to much lower than the first measured height 50 meter of the LiDAR. The sampling period and rate were 2 hours and 10 minutes, respectively.

Figs. 1 (a) and (b) show the instrumentation of AXYS WindSentinel™ and land-based LiDAR WINDCUBE v2, and the AXYS 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 200 m. Also, Fig. 1 (c) shows the specifications of two LiDAR systems.

Fig. 2 (a) presents the site of flume tests and setup of two LiDAR systems, and Fig. 2 (b) shows the front view of the AXYS WindSentinel™ under testing. Additionally, the AXYS WindSentinel™ was setup outside the lab to collect long-term data as shown in Fig. 2 (c).

### Harbor test

To simulate the wind measurement of LWS in real ocean condition, two LiDAR systems including buoy-mounted and land-based laser wind sensors, which were deployed at the Hsing-Da Harbor from October 16 to 25, 2013. The buoy-mounted laser wind sensor obtained from the AXYS WindSentinel™ was moored in the harbor, and land-based laser wind sensor called WINDCUBE v2 was placed at a flat terrain 500 meters away from the LWS. The sampling period and rate were 10 days and 10 minutes, respectively. The total number of wind data was about 1500.

Fig. 3 shows the site of validation at Hsing-Da Harbor and the instrumentation of WINDCUBE v2 and AXYS WindSentinel™. The distance between two LiDAR systems is about 500 meters surrounding with flat terrain and no building obstruction. Additionally, the WINDCUBE v2 was setup at the open space of fourth floor for the safety and management. The buoy was tied with two ropes to the nearby bollard which was a vertical short post serving as a permanent mooring system to decrease the wave impact shown in Fig. 3 (c).

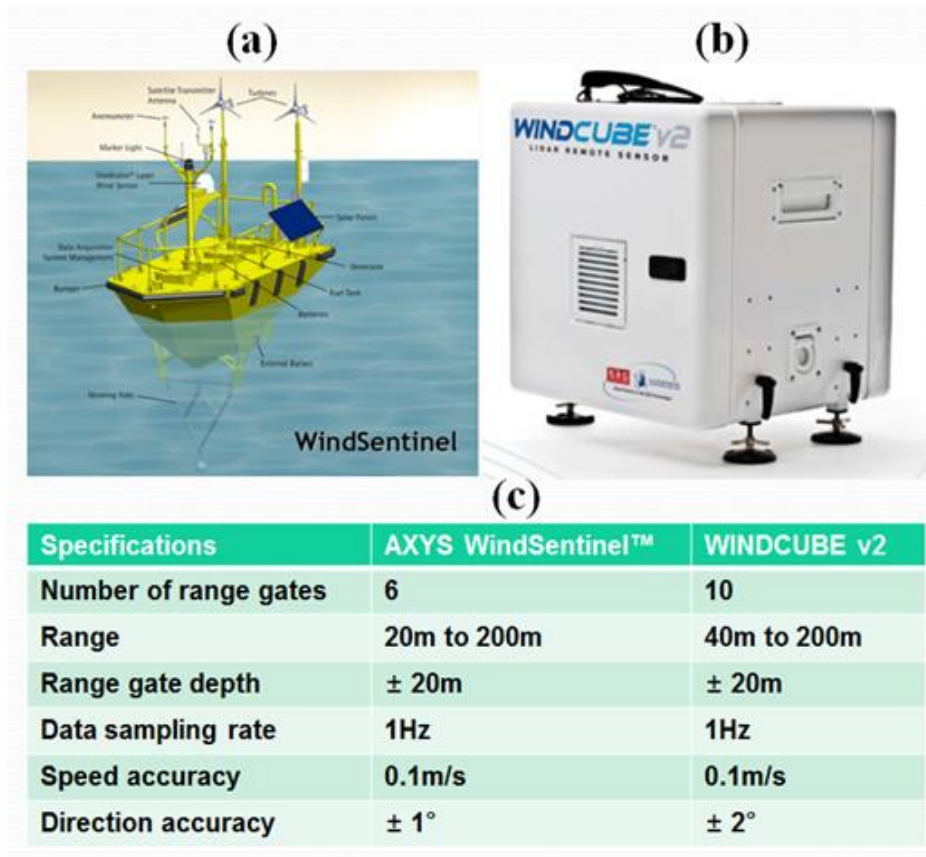


Figure 1. (a) AXYS WindSentinel™ (b) land-based LiDAR WINDCUBE v2 (c) the specifications of AXYS WindSentinel™ and WINDCUBE v2.

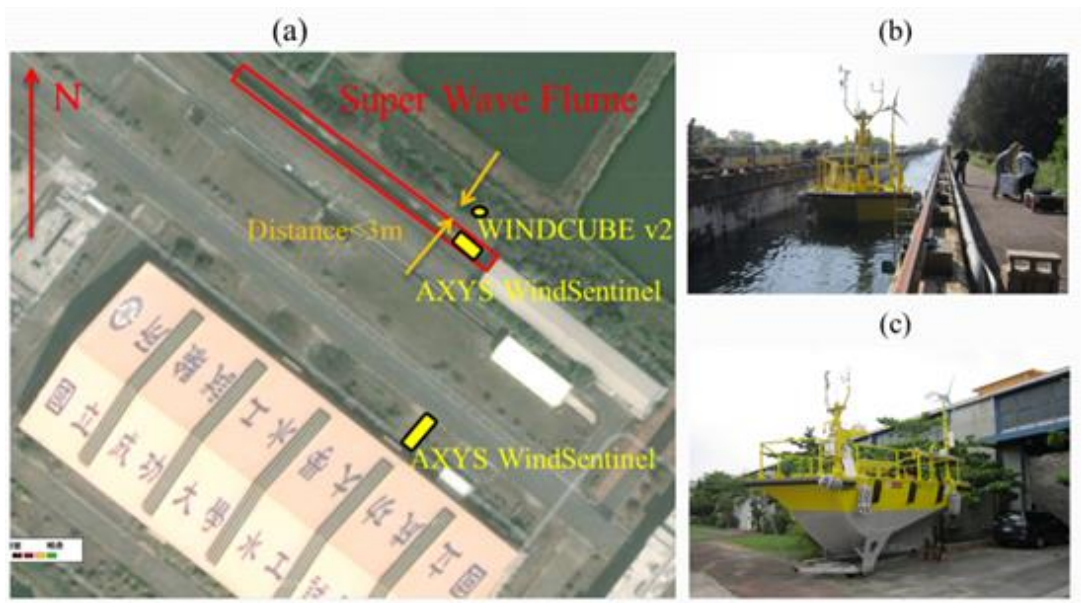


Figure 2. (a) The site of flume tests and setup of AXYS WindSentinel™ and WINDCUBE v2 (b) the front view of the AXYS WindSentinel™ (c) the deployment of the AXYS WindSentinel™ next to the laboratory of THL.

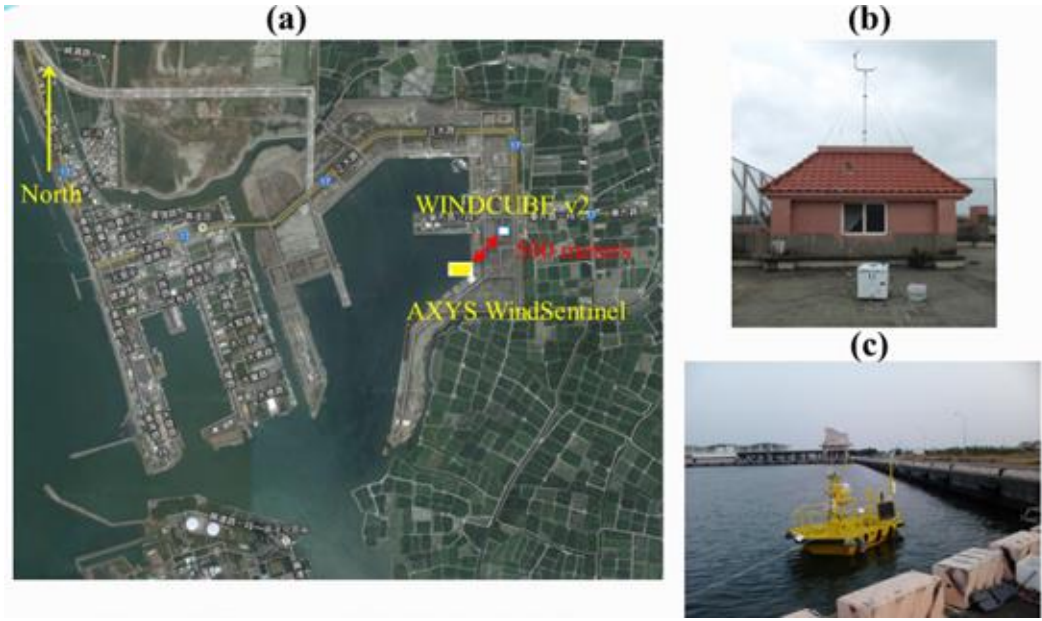


Figure 3. (a) The site of validation at Hsing-Da Harbor (b) the instrumentation of WINDCUBE v2 (c) the instrumentation of AXYS WindSentinel™.

#### DATA ANALYSIS

The average wind speed is the simple scalar average of the wind speed observations. A "unit-vector" average is used to calculate the average wind direction. In this technique, unity serves as the length of the vector, and the wind direction observations serve as the orientation of the vector. The  $u$  and  $v$  components are then calculated for each observation. Next, the average  $u$  and  $v$  components are computed and the average wind direction is derived from "arctan( $u/v$ ).". The calculated equations are shown below:

$$V_x = -\frac{1}{N} \sum \sin \theta_i \quad (1)$$

$$V_y = -\frac{1}{N} \sum \cos \theta_i \quad (2)$$

$$\bar{\theta} = \text{ArcTan}\left(\frac{V_x}{V_y}\right) \quad (3)$$

In which  $\theta_i$  the orientation of the vector,  $N$  the numbers of wind directions,  $V_x$  the averaging sine values of all directions,  $V_y$  the averaging cosine values of all directions,  $\bar{\theta}$  the averaging wind direction.

On the other hand, turbulence is important for the performance of the wind turbine. Measurement of turbulence intensity at hub height plays a significant role in wind resource assessment through the estimation of energy losses due to turbine wakes. Besides, it is also a key component of site classification and turbine selection studies. A measure of the turbulence level is given by the so-called turbulence intensity (TI) defined by the following equation:

$$TI = \frac{\sigma_u}{\bar{u}} \quad (4)$$

In which  $\sigma_u$  the standard deviation of mean wind speed,  $\bar{u}$  the mean wind speed.

## RESULTS AND DISCUSSION

The flume tests were conducted about 50 minutes on May 24, 2013, and a land-based LiDAR WINDCUBE v2 was used to compare and validate with the LWS. Fig. 4 (a) shows the time series of wind speeds at 200m in the test period, and the wind speeds range from 4 to 10 m/s. Fig. 4 (b) presents the time series of free surface elevation in the same period, and the measured wave heights and periods are about 0.55m and 9 sec, respectively. Fig. 4 (c) demonstrates the spectrum of wind speeds at 200m and free surface elevation. Due to the wave frequency is the reciprocal of the wave period equaling nearly to 0.11 Hz, Fig. 4 (c) shows the calibration of motion compensation is performed satisfactorily as the amplitude of wind speeds at 0.11 Hz is near zero. Additionally, Fig. 4 (c) shows the amplitude of the free surface is about 0.17 m, and a sideband is induced with the frequency and amplitude equaling 0.22 Hz and 0.07 m, respectively.

The 10-min mean wind speeds and directions of different elevations were averaged in the test period. Fig. 5 (a) shows both of the wind speed profiles are proportional to the elevation, and the wind speed range is about 1.3 m/s from 55 meter to 200 meter. Besides, both of the wind direction profiles are very uniform at different elevation shown in Fig. 5 (b). As a whole, despite the buoy was in motion under flume test, the results show two LiDAR systems are in a good agreement with great accuracy and reliability in wind measurement. For the discrepancy between two LiDAR systems, it comes from their different laser emission waveforms, including pulsed and continuous type, respectively.

The sampling rates of LWS and WINDCUBE v2 are ten minutes, and the total measured time interval in the test period are about 1,500. Thus, the measured wind data are reasonably enough for regression analysis.

Fig. 6 shows the regression results of wind speeds at different elevations between two LiDAR systems. The comparison of wind speeds shows a high correlation between two LiDAR systems.

Fig. 7 indicates the regression results of wind directions between two LiDAR systems. Most data points are at the regression line, and all the  $r$  square values are larger than 0.98. Overall, the regression results in Figs. 6 and 7 exhibit the excellent considerable confidence and accuracy in wind measurement.

Fig. 8 demonstrates the comparison of wind speed profiles between two LiDAR systems in the test period, and the higher agreements can be observed at different time instants. Obviously, most of the wind speed profiles below 10 m/s are nice.

Besides, to collect the long-term data of wind measurements, the AXYS WindSentinel™ was deployed next to the laboratory at THL in Taiwan. The period was from June 21, 2013 to October 25, 2013 for about three months, and the wind fields of three typhoon events are measured, including Typhoon Soulik, Typhoon Trami, and Typhoon Fitow, and the intensities of the three typhoon events were strong, weak, and moderate, respectively. Measurement of turbulence intensity (TI) at hub height plays a role in wind resource assessment through the estimation of energy losses due to turbine wake flows, and it is also a key factor of site classification and turbine selection. Fig. 9 shows the relationship between turbulence intensity and wind speed at 200 meters in three typhoon events. Fig. 9 (a) shows the local maximum TI of Typhoon Soulik is about 0.2, and it nearly doesn't change with wind speeds. Fig. 9 (b) shows the local maximum TI of Typhoon Trami is about 0.4, and no apparent correlation with the wind speed is observed. Fig. 9 (c) presents the local maximum TI of Typhoon Fitow is about 0.2, yet the TI is in inversely proportional with the wind speed below 2 m/s. Actually, the mean turbulence intensity of the three typhoon events is about 0.2. Besides, the local maximum turbulence intensities of Typhoon Trami and Fitow are 0.4 and 0.6, respectively.

Furthermore, due to the wind directions of typhoon structure outside the typhoon eye is counterclockwise inwardly. Figs. 10 (a)-(c) demonstrate the prevailing directions of three typhoon events are nearly northern.

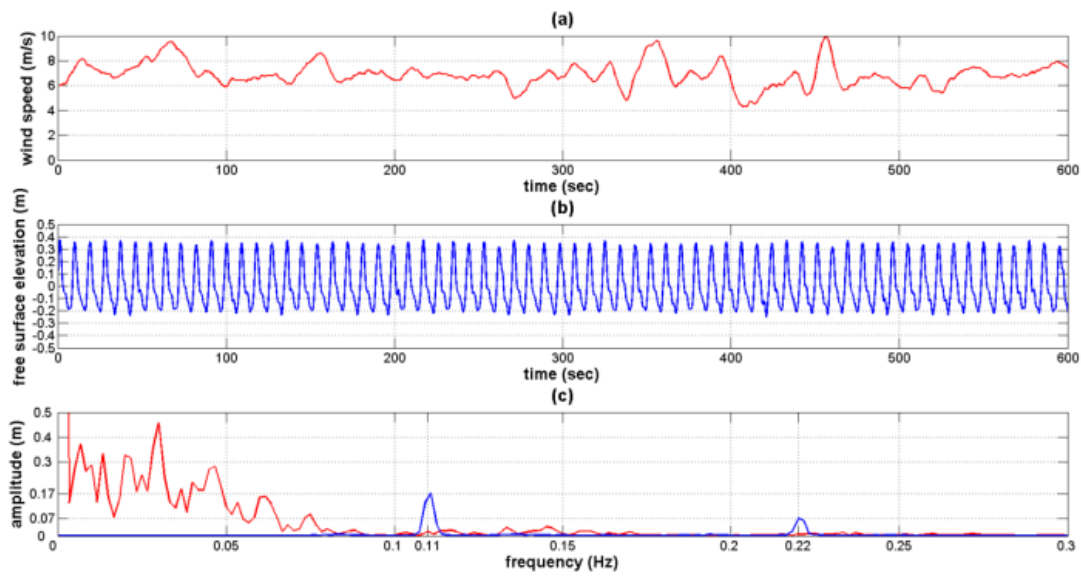


Figure 4. (a) The time series of wind speeds at 200m in 15:00-15:10 May 24, 2013 (b) time series of free surface elevation in the same period (c) spectrum of the wind speeds (red) and free surface elevation (blue).

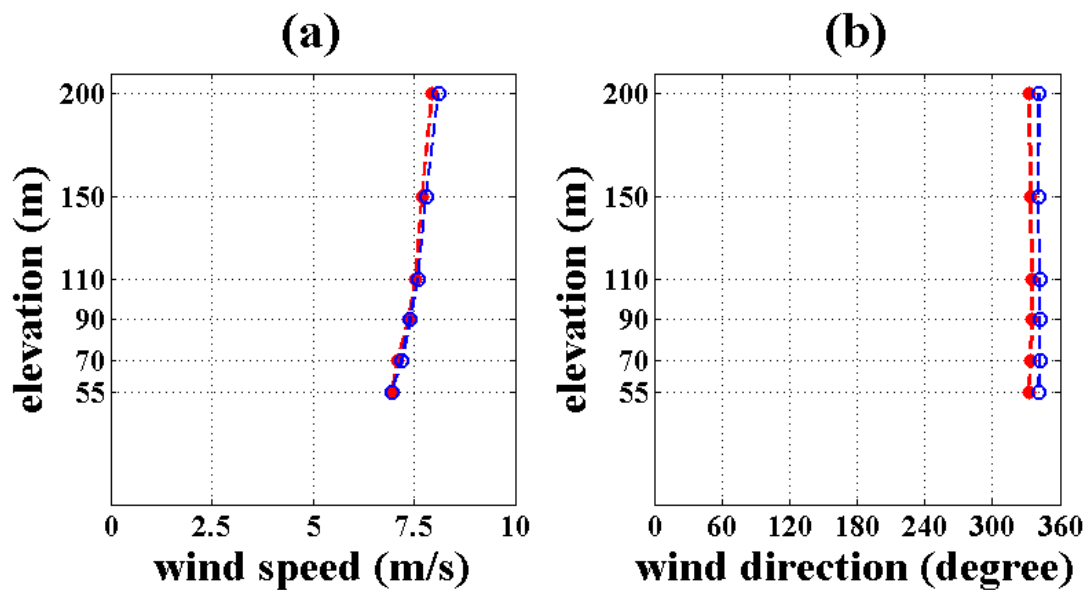


Figure 5. Comparison of wind speed and direction profiles between the LWS (red points) and WINDCUBE v2 (blue circles) (a) wind speed profiles (b) wind direction profiles.

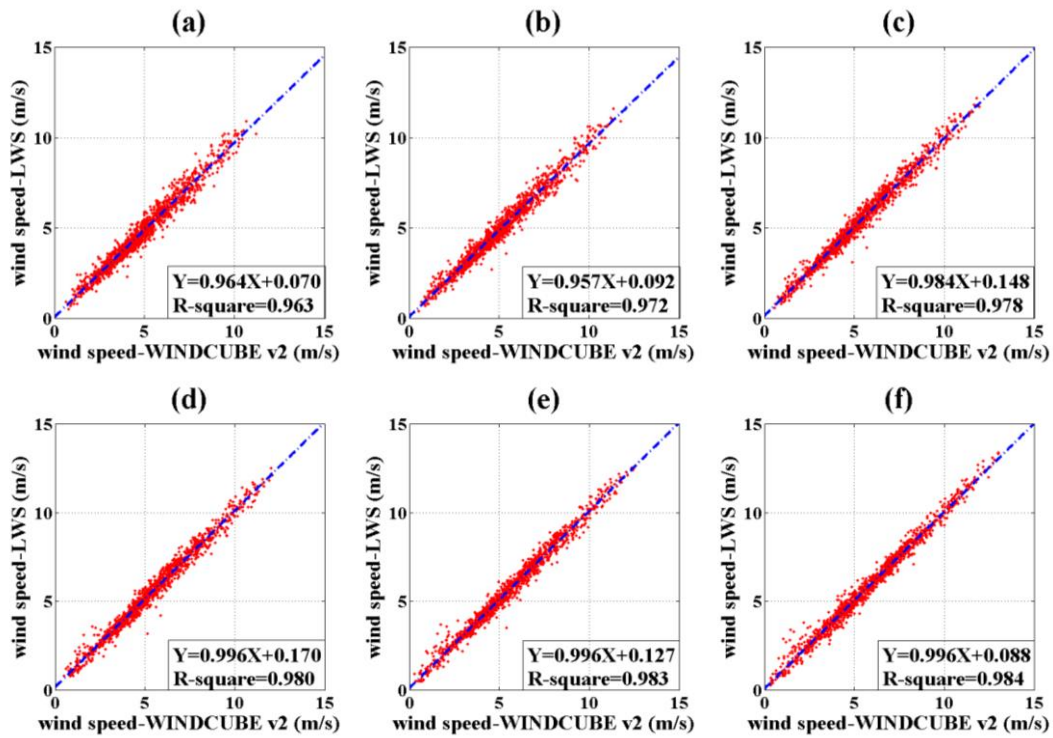


Figure 6. Comparison of wind speeds between LWS and WINDCUBE v2 (a)-(f) show the regression analysis from cell 1 to cell 6, respectively.

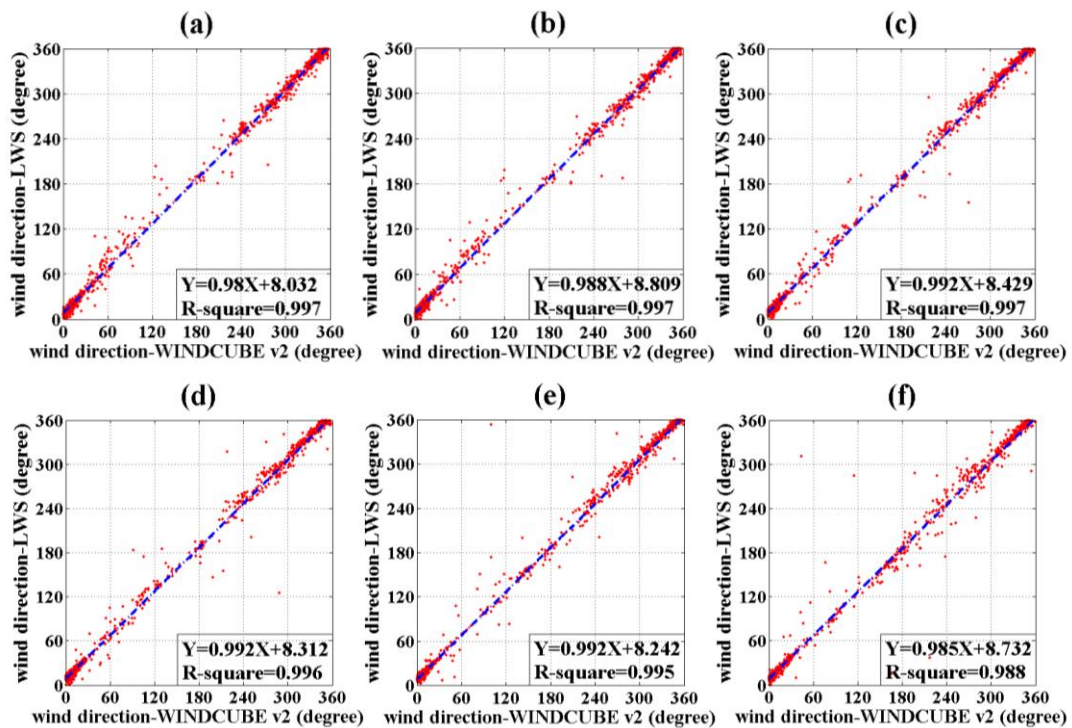


Figure 7. Comparison of wind directions between LWS and WINDCUBE v2 (a)-(f) show the regression analysis from cell 1 to cell 6, respectively.

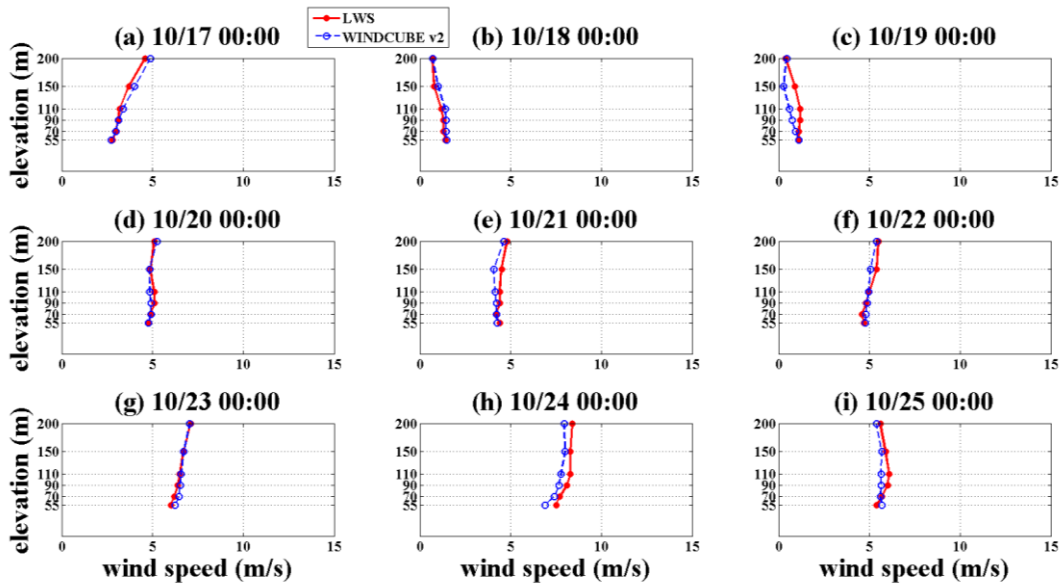


Figure 8 . Comparison of wind speed profiles between LWS (red points) and WINDCUBE v2 (blue circles) (a)-(i) show October 17th to October 25th , respectively.

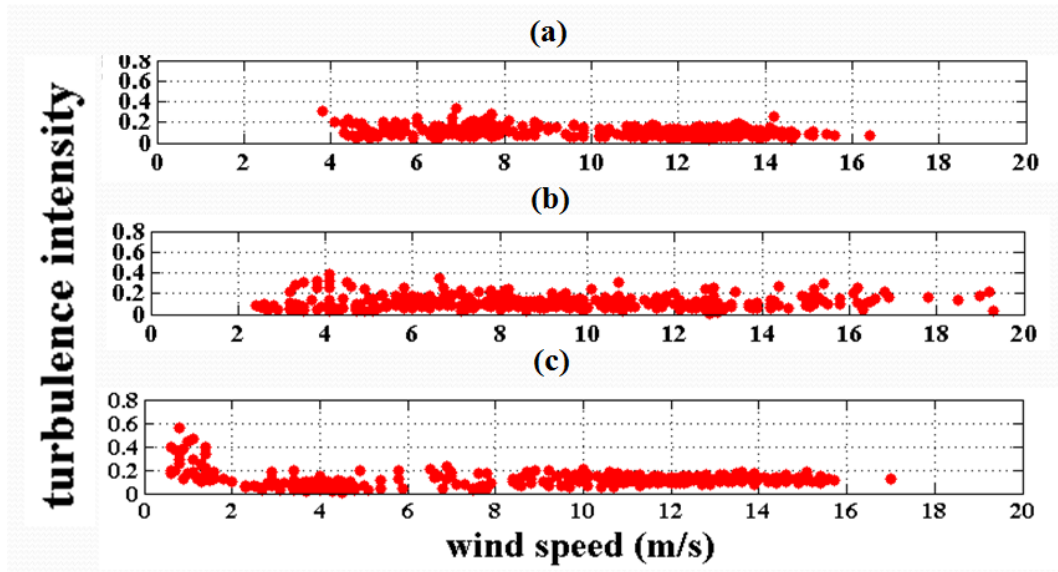


Figure 9 . The relationship between turbulence intensity and wind speed (a) Typhoon Soulik from July 11 to July 13, 2013 (b) Typhoon Trami from August 20 to August 22, 2013 (c) Typhoon Fitow from October 4 to October 7, 2013.

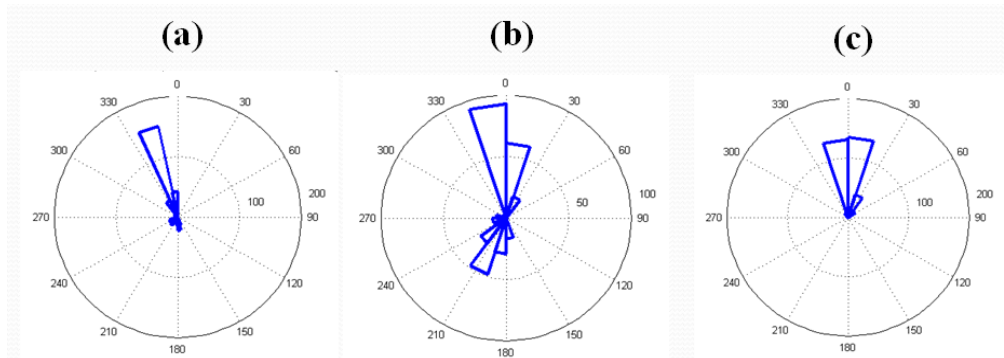


Figure 10 . The wind rose at 200 meters of three typhoon events (a) Typhoon Soulik from July 11 to July 13,2013 (b) Typhoon Trami from August 20 to August 22,2013 (c) Typhoon Fitow from October 4 to October 7, 2013.

## CONCLUDING REMARKS

Accurate wind profiling up to several hundred meters has been a significant issue for the wind resource assessment. Traditionally, the cup anemometer and wind vane were installed in the met mast to get wind data. Until now, the LiDAR technology has a great potential with higher accuracy and measurement range up to 2 km high. A laser wind sensor installed in the buoy of AXYS WindSentinel™, which can be applied to the offshore wind resource assessment was used in the campaign. A series of tests was conducted to show the performance and operation of the AXYS WindSentinel™ in this study.

In the flume test, the comparison of wind speed and direction profiles between two LiDAR systems shows a good agreement with high accuracy and reliability. Also, different laser emission waveforms account for the small discrepancy between two LiDAR systems. In the harbor test, the regression results of wind speeds and directions show a high correlation up to 0.99 between two LiDAR systems.

Also, three measured typhoon events show the mean turbulence intensity was about 0.2 and inversely proportional to the wind speed below 2 m/s.

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