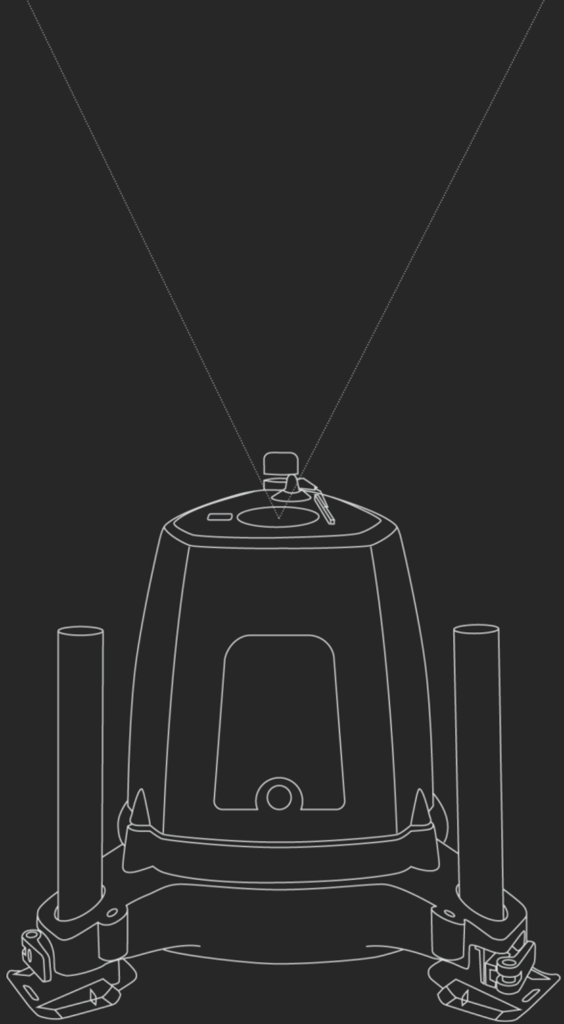
PERFORMANCE STABILITY OF ZEPHIR IN HIGH MOTION ENVIRONMENTS:

FLOATING AND TURBINE MOUNTED



M. Pitter, E. Burin des Roziers, J. Medley,

M. Mangat, C. Slinger and M. Harris

October 2014

E sales@zephirlidar.com
T +44 (0) 1531 650 757

The Old Barns • Fairoaks Farm
Hollybush • Ledbury • HR8 1EU • UK

TABLE OF CONTENTS

ABSTRACT

This paper discusses the stability of ZephIR performance for two cases where the lidar is subject to extreme motion, namely when mounted on a floating offshore platform or on a wind turbine nacelle or spinner. Remote wind sensors such as sodars and lidars use either sound or light waves to measure the line-of-sight velocity of the wind. The relationship between the line-of-sight velocity and the wind vector depends on the direction in which the beam is pointing, so any rotational motion of the sensor (roll, pitch or yaw) may affect wind measurement. In addition, translational motions of a remote sensor (surge, sway or heave) can bias the measurement of the wind.

It is demonstrated by simulations, controlled experimental studies and the results of field deployments that the effect of motion on ZephIR performance is insignificant and easily compensated, largely due to the high-resolution, fast data rates and multiple viewing angles enabled by the very high carrier to noise ratio unique to continuous wave wind lidars, such as ZephIR.

1 INTRODUCTION

Remote sensing on floating offshore platforms such as buoys, barges and ships provides a cost effective alternative to expensive foundation-mounted offshore wind monitoring towers for wind resource assessment [1][2]. In addition, it is unlikely that foundation-mounted offshore meteorological masts will ever be viable in water depths of over 30 m, whereas floating platforms, depending on their design, can be deployed in essentially any water depth. This will become particularly relevant as floating wind turbines in deep offshore waters start to come online.

Another growing application for wind lidars is to deploy them on the nacelle or in the spinner of wind turbine generators (WTGs). This can be useful for power performance validation, turbine health-checking, yaw misalignment calculations, feed-forward wind turbine control and various research topics such as wake measurement.

Both of the applications described above can subject the remote sensor to motion. Buoys typically exhibit translational (surge, sway and heave) and rotational motions (pitch, roll and yaw). Wind turbines are tilted backwards by the wind, and also “nod” (pitch) at the resonant frequency of the tower structure. In addition, they experience small amounts of “naying” (roll). All of these motions have the potential to adversely affect the measurement of the wind vector. In the following sections the effect of motion on remote sensor performance and in particular the ZephIR 300 and ZephIR DM (Dual Mode) continuous wave wind lidars will be described. In addition it will be demonstrated by theory, experimental results and field trials that these motions can be tolerated, or the measurement methodology adapted such that their effect on the accuracy and precision of the wind measurement can be negligible, a unique property of the continuous wave architecture found in all ZephIR lidars.

2 TYPES OF REMOTE WIND SENSORS

There are three main types of remote wind sensor currently in widespread use in the wind and meteorology industries today: sodars [3], which use audible sound waves, coherent Doppler lidars [4][5][6], which use short-wavelength infrared light, and incoherent Doppler lidars [7], which typically operate in the ultraviolet.

Since sodars use sound waves (velocity of around 340 ms^{-1}) there is an appreciable time delay between transmit and receive, on the scale of typical buoy or turbine nacelle movement, which in the presence of motion misaligns the device badly enough to render their use impractical. Incoherent laser radars are generally not eye safe and often use very delicate optical etalons to determine the wind speed, so they too are generally unsuitable for wind resource assessment from a moving platform. In addition, neither sodars nor incoherent laser radars are currently accredited to provide finance grade wind resource data.

For these reasons, sodars and incoherent laser radars will not be considered further in this paper for deployment in high motion environments such as floating offshore or turbine spinner mounted.

Lidars, since they use light, do not suffer from the same time-of-flight limitation as sodars. There are currently two types of finance-grade (DNV GL Stage 3) wind lidar on the market, continuous wave (CW) [4][5] and pulsed [4][6]. They are both termed Doppler lidar, that is, they sense the Doppler shift of the received light and use this to calculate the wind parameters, but they differ in their measurement methodology.

CW lidars use focussing to determine the measurement height or range, whereas pulsed systems use time-of-flight. The ZephIR is a CW design so this paper concentrates on the effect of motion on this methodology. However, where appropriate, the characteristics of pulsed systems in the presence of motion will be compared to and contrasted with CW.

For example:

- CW lidars measure the wind speed at user defined heights in a sequential fashion. All of the available laser energy is focussed at the user defined measurement height leading to a high carrier-to-noise-ratio (CNR) and consequently very high line-of-sight velocity data rates (400 Hz has been achieved in customised versions of the ZephIR, while 50 Hz is the standard rate for production units). This leads to 50 line-of-sight data points being acquired during a 1-second scan at each height. The nature of buoy and turbine motion is such that very little movement occurs over the 20 ms required for each line-of-sight measurement, and even over the 1-second required to measure at each height, the motion is limited. Pulsed systems on the other hand take between 0.75 s and 1 s to measure a single azimuth line-of-sight velocity, and the light used to acquire the measurements is effectively spread over all the heights (pulsed system use collimated or very weakly focused light).

- Pulsed systems generally use ‘staring mode’. That is, during the typically 1-second measurement at a particular azimuth and elevation, the beam is stationary, whereas CW systems continually scan the beam around a disc while focussing at a particular height. In addition, due to the low peak powers of CW lasers and the damage thresholds of optical fibres, CW lasers used in lidar typically have an average power output of around ten times that of pulsed systems and hence a much more favourable photon budget.

- CW systems are inherently simple in design, and fewer system interconnections ensure minimal loss in the various fibre optic components delivering maximum sensitivity.

- The simple CW design extends the service interval out to 3 years with no intermediate servicing or calibration required during this period This is an important consideration offshore, where visits to the buoy are constrained by unpredictable weather conditions and can be very costly, and also when mounted on a turbine where any downtime associated with taking a turbine out of service impacts wind farm production.

3 THE EFFECT OF BUOY MOTION ON ZEPHIR PERFORMANCE

To summarise, translational motions (sway, surge and heave, along the x, y and z axes respectively) simply add an additional motion vector to the true wind vector. Rotational motions (roll, pitch and yaw, around the x, y and z axes respectively) can induce errors in the line-of-sight speed measurement due to the tilting or yawing of the system affecting the angle between the wind vector and the measurement beam vector. The remainder of this section investigates and quantifies these effects in more detail.

3.1 Buoy yaw

Since remote wind sensors measure wind direction relative to their physical orientation, yaw will obviously affect the measurement of wind direction. For the ZephIR, this is the simplest motion to accurately correct for. A well calibrated yaw sensor can acquire the actual heading of the buoy, and this can be added to the ZephIR direction measurement to obtain the correct value. If the buoy yawing is fairly rapid, such as may be the case for a wave buoy, the yaw data should be obtained at 1 Hz and used to correct each of the individual 1-second scans. At the end of the 10-minute averaged period, the corrected directions can then be unit-vector-averaged to produce a precise, industry standard wind direction measurement. If the yaw is slow, such as that induced by tidal action on a spar or tension leg buoy, then a 10-minute average obtained from the yaw sensor can be used to correct the 10-minute ZephIR measurement.

It should be noted that a well-calibrated compass is required for yaw measurement. Since buoys typically have a certain amount of both hard and soft magnetism, the compass may not read true. However compass calibration is a well used and understood process. Most off-the-shelf electronic compasses include an automatic compensation routine, or calibration can be carried out manually prior to deployment.

3.2 Buoy pitch and roll

Roll and pitch affect the model assumptions used to calculate wind vectors from line-of-sight speeds since they change the angle at which the laser beam impinges on the wind vector. The overall effect of this is to produce a small negative bias that depends on the magnitude of the tilt and its relationship with the wind direction. In an early theoretical study [8], Wolken-Möhlmann *et al* showed by simulation that both CW and pulsed systems were affected by tilt. Two cases were examined; case 1, where there was a 75.4% probability for the tilting angle in x-direction of being under 5° and a 21.5% probability of between 5° and 10°. For the second simulation (case2) the respective probabilities were 44.9% and 30.5%.This meant that the highest 10% of all tilting occurrences in the x-direction exceeded 7.2° and 14.4°, respectively. The simulated sea state had significant wave heights of between 0.75 m and 2.5 m and horizontal wind speeds at 60 m height of between 3 ms^{-1} and 15 ms^{-1}. For cases 1 and 2, the simulation showed a root mean square error (RMSE) of 0.386 ms^{-1} and 0.566 ms^{-1} respectively for a CW lidar. This compares to an RMSE for a fixed (stationary) CW lidar of 0.364 ms^{-1}. The 4-beam pulsed system fared less well with RMSEs of 1.481 ms^{-1} and 2.734 ms^{-1} respectively. Wolken-Möhlmann *et al* ascribed this difference to the large number of different scanning directions (50) in the CW system, and the fact that the pulsed system, due to the long measurement time, could only be corrected over at least 0.5 s of data [8].

The worst case scenario for rotation is actually a static tilt along the same axis as the wind direction. This is because, for periodic tilts, as typically experienced by buoys, the lidar does not spend very long at the largest tilt values, but spends a good deal of time pointing near vertically. Figure 1 below shows the relationship between static tilt and wind direction for a ZephIR lidar. It can be seen from Figure 1 that when the wind is orthogonal to the tilt, then no bias is introduced, regardless of the magnitude of the tilt. For static tilts of 5° or less that are aligned with the wind vector, the bias is less than 1%, reaching around 1.5% at 10° and 5% at 15°. For periodic tilts, these values reduce by approximately 50% due to the fact that the ZephIR spends little measurement time at these extreme tilt values.

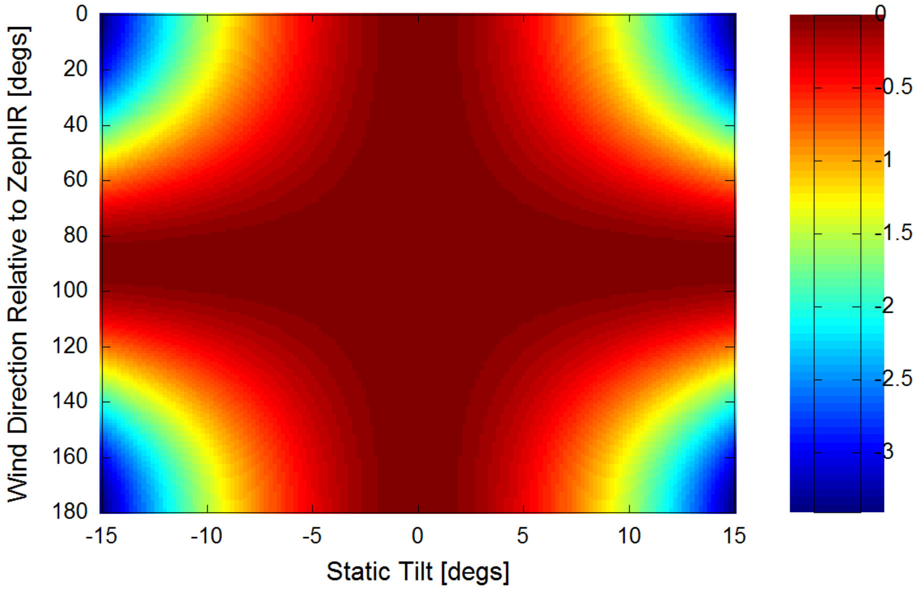


Figure 1: ZephIR wind measurement bias (% - indicated by the colour bar) as a function of ZephIR static tilt angle and wind direction.

The results in Figure 1 show that the worst case scenario for a buoy mounted ZephIR experiencing period pitching or rolling of 10° or less would be an under read (negative bias) of around 0.75%. The use of motion sensors can be used to correct this bias, or, on more stable platforms such as spar and tension leg buoys, to simply filter out data for periods when the tilt exceeds predetermined limits. In practice, spar and tension leg buoys do not exhibit enough motion to bias the wind speed measurements to any appreciable amount since they are typically limited to periodic motion of less than 5°, leading to a bias of less than 0.25% when the results are averaged around the wind rose. A recent experiment on the effects of static tilt showed that regression parameters of R^2 of 0.993, 0.992 and 0.991 with gradients of 1.001, 0.998 and 0.992 were achieved by ZephIRs with fixed tilts of 0°, 5° and 10° respectively [9].

While it is possible to stabilise a lidar to some extent by using a mechanical gimbal, this has never been found to be necessary for buoy-mounted ZephIR deployments. However, all commercially available buoy lidars based on pulsed systems use mechanical gimbals, which inherently increases the cost and possible points of failure of the overall system.

3.3 Buoy translational movement

The effect of surge, sway and heave on the wind measurement is simply to add a motion vector to the measured wind vector. For example, if the wind is at 10 ms^{-1} from the south and the buoy is moving north at 1 ms^{-1}, a wind speed of 11 ms^{-1} will be measured. This is the case for both pulsed and CW lidars and is easily compensated by using an inertial measurement unit to record the buoy motions and simply subtract the motion vector from the measured wind vector.

If only 10-minute averaged wind velocities are required, the motion compensation is unnecessary for CW lidars such as the ZephIR. Since buoy motion is periodic of typical frequency between 0.1 and 0.25 Hz, the motion induced errors in the measurements average to zero over a 10-minute period and excellent results can be obtained without motion compensation [1].

3.4 Motion effect controlled experiments

Work has been carried out at the Christian Michelsen Research Institute in Norway to investigate the performance of CW (ZephIR 300) and pulsed lidars under the types of motions typically experienced by wave buoys [10]. A powerful motion stage was used to simulate all the possible motions experienced by a buoy mounted lidar, both individually and in combination. In each test, the ZephIR outperformed the pulsed lidar in terms of measurement accuracy. A selection of results for the ZephIR 300 while undergoing pitch and roll motions of up 5° are shown in Figure 2 below. It can be seen that the ZephIR 300 performed excellently in the presence of pitch and roll, exhibiting very good accuracy and precision in the 10-minute averaged data.

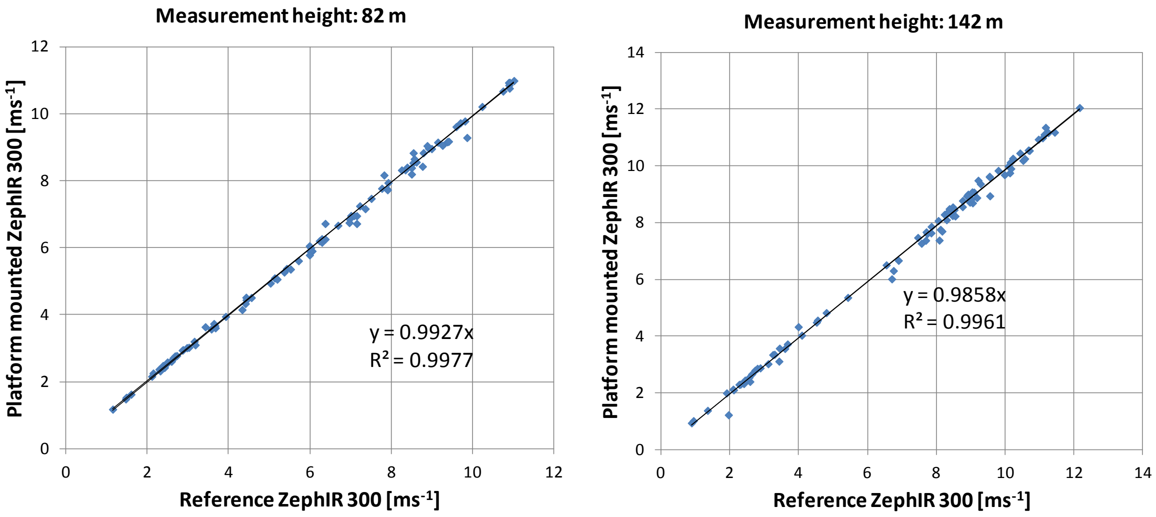


Figure 2: Correlation plots of Z300 CW lidar mounted on a motion platform and a ground based CW lidar. The platform mounted lidar was subject to periodic pitch and roll motions of up to 5° amplitude.

Full details and results of this trial can be found in [10] and [11]. Based on these results, Fugro Oceanor selected a ZephIR 300 as the measurement device for their SeaWatch buoy lidar [12].

3.5 Buoy mounted ZephIR deployments

ZephIRs are now being deployed by a range of buoy manufacturers to measure wind parameters offshore. Deployments that are now in the public domain include SeaRoc's SeaZephIR, Babcock's FORECAST and Fugro's SeaWatch (see Figure 3 below) and several other projects are reaching advanced stages of development and testing, with still further projects at the planning stage.

Figure 3: From left to right; SeaRoc's SeaZephIR tension leg buoy, Babcock's FORECAST spar buoy and Fugro's SeaWatch wave buoy.

The SeaZephIR is a tension leg buoy, a design that practically eliminates motion from the instrument platform and has delivered very precise and accurate wind data without the need for any mechanical gimbals or software motion compensation.

The Babcock FORECAST is a low motion spar buoy which, in common with the SeaZephIR, reduces motion to a level where compensation (other than yaw for wind direction) is unnecessary to achieve excellent accuracy and precision. In a recent offshore trial in the Irish Sea off the north coast of Wales, regression parameters of R^2 = 0.990 and a gradient of 1.006 and R^2 = 0.990, gradient of 0.991 were achieved for forced (one parameter fit) and unforced (two parameter fit) respectively at a measurement height of 90 m compared to the mast at Gwynt Y Môr [13] (Figure 4). The lidar and mast were separated by 260m. The first stage of the trial produced very high quality data but problems with the power supply severely affected data and system availability. Since the power supply problems have been fixed however, at the time of publishing this paper, system availability has been 100% and data availability has been greater than 99% at all measurement heights.

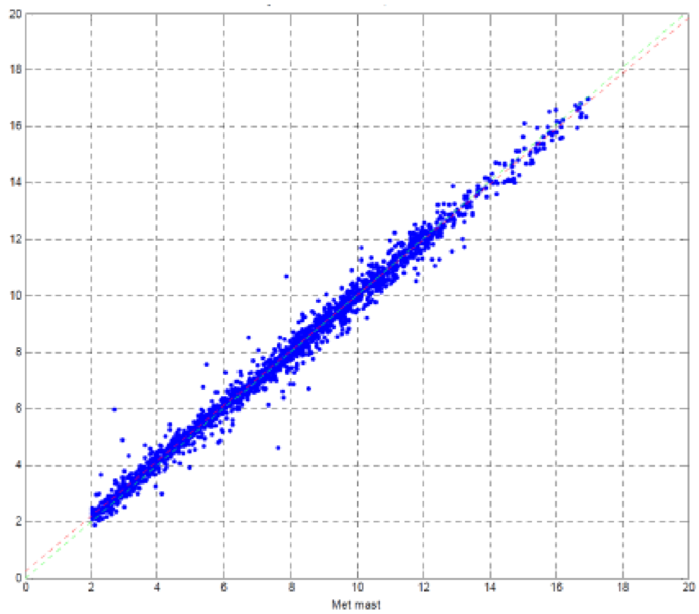


Figure 4: Babcock buoy wind speed correlation at 90 m at Gwynt Y Môr

3.6 Summary of buoy motion effects on ZephIR performance

It can be seen from both simulations and offshore trials that the 10-minute averaged wind speed recorded by ZephIRs is very resilient to the presence of the type of motion experienced by a range of buoy designs, even when no mechanical stabilisation or software compensation is applied. Yaw is easily compensated by using a compass to determine the actual ZephIR bearing at the time of the measurement; translation motions tend to average to zero over 10-minutes and do not degrade the results, and modest periodic tilts only introduce a very small negative bias.

4 THE EFFECT OF WIND TURBINE MOTION ON ZEPHIR PERFORMANCE

An increasingly widespread and important class of application of wind lidar involves deploying the lidar on a wind turbine generator nacelle or in the rotor spinner. These configurations are typically used for power performance measurement, yaw misalignment measurements, turbine health-checking, turbine feed-forward control or a variety of research topics such as wake investigations. Turbines do not tend to move as much as buoys, however they do “nod” (pitch) and “nay” (roll) when subjected to strong winds.

4.1 Wind turbine nodding

Fore-aft, pitching motion of a wind turbine generator has two components; a resonant oscillation of typically 0.1 to 0.3 Hz, and a wind induced tilt that increases up to typically 4° or 5° at the WTG rated wind speed, then slightly reduces at higher speeds as the rotor blades are feathered [14][15].

The amplitude of the resonant component of the tilt is small, but can cause a lidar velocity of a few tenths of a ms^{-1}. The wind induced tilt leads to a change in both the beam pointing direction, and the height above the ground at which the measurement is made at a given range [15].

The velocity component can be easily dealt with by measuring the lidar velocity and subtracting it from the measured wind velocity. As with buoy motion, this component tends to average to zero over a 10-minute period and not affect averaged wind data. The ZephIR DM (Dual Mode), a model designed to work both on WTGs or on the ground, has a built in velocity sensor to effect this correction.

The wind induced tilt can be more problematic. For WTG power performance, IEC recommendations are that wind speed is measured at hub height and at a distance of at least 2 rotor diameters (2D). Once probe length effects are taken into account, this means that both pulsed and CW lidar need to measure at a range of around 2.5D which can approach 300 m on a modern offshore WTG. For a “staring” mode lidar, a tilt of 5° causes the height of the measurement to change by over 25 m. This effect can be minimised by pointing the lidar below hub height while the wind is at 0 ms^{-1} such that the error in height becomes ±12.5 m, but this can still be an appreciable fraction of the hub height and lead to inaccurate and wind shear dependent measurement errors.

The ZephIR overcomes this problem by scanning the beam around the full 360° while measuring the inclination with a built in high precision inclinometer. Hence, whatever the lidar tilt, there is line-of-sight data with a known inclination angle at heights that can be spread around the entire rotor. It is then a simple matter to remove the effect of this tilt.

Figure 5: ZephIR DM installed on a Vestas wind turbine with RES

4.2 Wind turbine naying

As well as nodding, turbines also exhibit side-to-side movement (naying, or roll). This is typically around an order of magnitude less than the nodding motion in amplitude, but can still cause the beam to point in a slightly different direction than that assumed by the signal processing algorithms and lead to errors in wind measurement.

To overcome this, the ZephIR DM has a built-in roll sensor so the beam pointing direction is precisely known and accounted for at all times.

5 CONCLUSIONS

Remote wind sensing devices can be subject to a range of motions when deployed on either a buoy or a WTG. If not understood or compensated for, these motions can lead to a lack of accuracy and precision in the wind vector measured by a remote sensor.

A measurement methodology, made possible by the very fast high-resolution data rate of the ZephIR 300 and ZephIR DM wind lidars, renders them very resilient to most motion effects. It enables straightforward and transparent compensation for the motions that could otherwise still lead to measurement error. This is demonstrated clearly through a complete range of theoretical, practical and commercial projects documented within this paper.

6 REFERENCES

[1] Rogers, T., Briggs, K., Randall, G., Hughes, H., *Remote Sensing on Moving Offshore Platforms*, Proceedings of EWEA 2011, Brussels, Belgium.

[2] Virginia Department of Mines, Minerals and Energy, *Meteological Tower Placement Report to the Virginia Offshore Wind Development Authority (VOWDA)*, 2010.

[3] Bradley, S., Mikkelsen, T., *SODAR Remote Sensing*, International Sustainable Energy Review, **5**(2), pp 38, 2011.

[4] Clifton, A., *Remote sensing of wind by Doppler Lidar for wind energy applications*, Introduction to Lidar 111, NREL, 2013.

[5] Pitter, M., Slinger, C., Harris, M., *Remote Sensing for Wind Energy, 3rd Edition, Chapter 3, Introduction to continuous-wave Doppler lidar*, DTU Wind Energy-E-Report-0029, 2013.

[6] Cariou, J-P., *Remote Sensing for Wind Energy, 3rd Edition, Chapter 4, Pulsed lidar*, DTU Wind Energy-E-Report-0029, 2013.

[7] Abreu, V.J., Barnes, J.E., Hays, P.B., *Observations of winds with an incoherent lidar detector*, Applied Optics **31**(22), 1992.

[8] Wolken-Möhlmann, G., Lilov, H., Lange, B., *Simulation of motion induced measurement errors for wind measurements using lidar on floating platforms*, Proceedings of iSARS 2010, Paris, France.

[9] Mangat, M., Burin des Roziers, E., Medley, J., Pitter, M., Harris, M., *The Impact of Tilt and Inflow Angle on Ground Based Lidar Wind Measurements*, Poster and paper, EWEA, Spain, 2014.

[10] Hellevang, J.O., *Effect of wave motion on wind lidar measurements – Comparison testing with controlled motion applied*, DeepWind 2013 – 10th Deep Sea Offshore Wind R&D Conference, Trondheim, Norway.

[11] Report prepared by CMR, University of Bergen, Statoil, Marintek and Fugro OCEANOR, *Measurements of Wind Profile from a Buoy using Lidar Final Report*, Reference No: 9631, 5 June 2012.

[12] Fugro Oceanor, *SEAWATCH Wind LiDAR Buoy Brochure*, 2012

[13] McConville, C., *Floating LiDAR Overview*, All-Energy 2014, Aberdeen, UK.

[14] Rutherford, A., Pitter, M., Slinger, C., Burin des Roziers, E., Barker, W., Harris, M., *The Effect of Motion on Continuous Wave Lidar Wind Measurements*, Windpower 2013, Chicago, USA.

[15] Wagner, R., Courtney, M., Pedersen, T.F., *Power Performance Measured Using a Nacelle-mounted LiDAR*, DEWI Magazime (43), 2013.