Continuous wave wind Lidars: all heights, all terrains, always available and for all turbine rotors

A wind Lidar is quite simply a remarkable piece of technology recently described by Avangrid as having 'advanced the wind industry globally'. Generic Lidar benefits are summarised by Renewable Energy Systems (RES) as being 'safer, cheaper, better, faster' than traditional meteorological masts.

An invisible, eye-safe beam of light interrogates the sky above at user defined heights and determines the characteristics of the wind in order to advise and improve wind and meteorological industry understanding around the world, onshore and offshore, on fixed and floating structures.

Continuous Wave (CW) Lidars are able to achieve something unique in addition; this is due to their on-board ruggedized focussing system that allows for the following features:

1. All the laser power is focussed at each specific measurement distance ensuring very high sensitivity which in turn allows wind measurements to be rapidly integrated over short periods of times on moving platforms e.g. floating Lidar applications, or when the wind flow is changing rapidly, such as in complex flow, and equally over large areas when scanning the larger wind field, for wind turbine performance measurements and control.
2. In all applications the focussing of the laser also ensures maximum availability that is not subject to the range being interrogated i.e. availability is not height dependent.
3. An unparalleled range of measurements can be taken from the installed location (~1m Above Ground Level) from just 10 metres and up to 300 metres.

These unique features of CW Lidar are described and evidenced below, beginning with vertical profiling use cases.

All heights

A novel approach to wind measurements can often provide the best approach when project-specific factors such as cost, complexity of terrain or time are taken into account. Continuous Wave Lidars deliver flexibility in this regard by measuring across a very broad range of heights, from ground-level up to 200 metres and beyond, up to 300 metres in certain applications. Two examples are discussed below.

Very short met masts combined with roaming CW Lidar

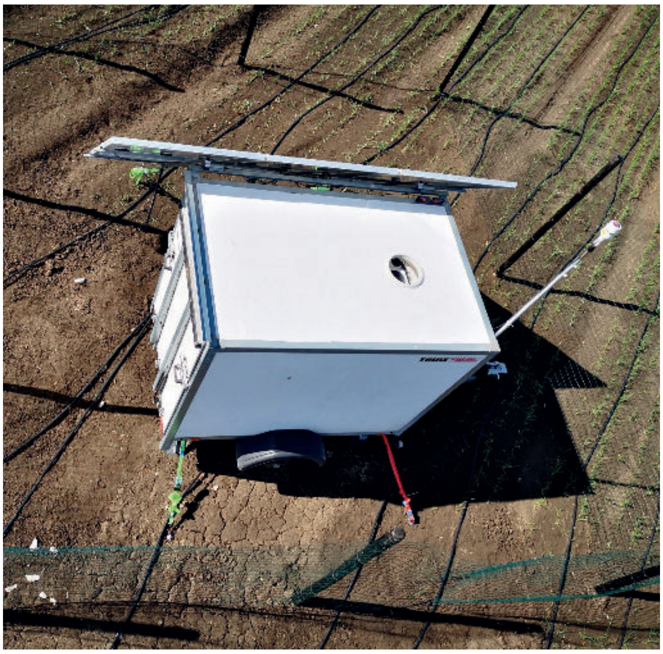
A new wind measurement campaign is underway in western Greece as part of a major renewable energy power project. Istos Renewables Ltd. is performing the wind measurement programme using a ZX 300 Lidar together with very short 30-metre-high wind data reference masts. Recording wind data across the full turbine rotor and beyond top tip height of even the largest wind turbines, the ZX 300 Lidar eliminates the need for a full scale conventional meteorological mast approach.

The combination of a roaming Lidar with only a very short met mast as a fixed, long-term, secondary reference, this bankable methodology cuts cost, reduces the need for working at height and makes establishing the wind profile across the whole site far less time consuming.

With a low visual impact, the low height approach to measurement equipment helps to curb potentially significant business risks while simultaneously reducing project uncertainty. The flexibility afforded by a mobile Lidar unit also gives developers an opportunity to fully explore the wind potential of a site.

Recording at four locations, the latest

Figure 1: Low visual impact solution with ZX 300 sited in trailer next to short 30m met mast.



Typical trailer installation

measurement campaign from Istos is to form a key part of the development of an approximately 160 MW wind power installation that is planned for the location.

Data obtained during the analysis period will support the optimisation of the project both in terms of the final layout and the selection of the ideal wind turbine model, including the rotor diameter and its rated generation capacity.

In addition, while the complex and rocky terrain found in this part of Greece and mountainous regions elsewhere can be challenging for wind measurement, the advanced data capture from a 50Hz Continuous Wave scanning Lidar such as ZX 300 ensures a high degree of accuracy is possible even in the most difficult scenarios.

Very tall met mast validations with CW Lidar

In contrast with the previous case study, a two-year measurement campaign of a vertical profiling continuous-wave (CW) focusing wind Lidar has been carried out by the Royal Netherlands Meteorological Institute (KNMI) at Cabauw, the Netherlands.

Data availability and data quality of the wind Lidar under various meteorological conditions was compared with in situ wind measurements at several heights on the 213m tall meteorological mast.

An overall availability of quality controlled wind Lidar data of 97% - 98% was achieved across the two-year period. Within the wind energy industry wind Lidars are typically validated between 4 m/s and 16 m/s and for this range of wind speeds the correlation gradient against the mast was between 0.99 - 1.00, with 1 corresponding to theoretical perfect agreement. The 'scatter' of measurements observed was low, with R2 values better than 0.996. These measurements equate to a bias in the horizontal wind speed of just 0.03 - 0.13 m/s. The mean bias in the wind direction is within 2°, which is on the same order as the combined uncertainty in the alignment of the wind Lidars and the mast wind vanes.

This combination of low and high measurements, with proven performance throughout creates a very flexible approach to projects that utilise CW Lidars.

Always available

Further to the above study performed by KNMI, more than 500 individual performance validations of Continuous Wave Lidars at the UK Remote Sensing Test Site have been conducted that specifically investigate the performance across all measurement heights with respect to data availability and accuracy (limited to a maximum of 91 metres due to the mast height) and the summary of results is presented in Figures 2 and 3:

Combined results from >500 ZX300 performance verifications - Data Availability		
Height (m)	**Data Availability %**	
(m)	*Mean*	*Std Dev*
180	99.00%	0.8
160	99.10%	0.9
140	99.30%	0.9
105	99.50%	0.9
91	98.20%	1.4
70	98.80%	1.1
45	99.00%	1
20	99.10%	1.2

Figure 2: Statistical analysis of data availability of a batch of over 500 ZephIR / ZX 300 performance verifications from the UK Remote Sensing Test Site.

Combined results from >500 ZephIR 300 performance verifications - Horizontal wind speeds				
Height (m)	**Gradient**		**R2**	
(m)	*Mean*	*Std Dev*	*Mean*	*Std Dev*
91	1.002	0.007	0.990	0.006
70	1.001	0.005	0.992	0.006
45	1.000	0.005	0.993	0.006
20	0.998	0.005	0.993	0.006

Figure 3: Statistical analysis of horizontal wind speed of a batch of over 500 ZephIR / ZX 300 performance verifications from the UK Remote Sensing Test Site.

As reported above, the constant high sensitivity of CW Lidar ensures high levels of data availability. ZephIR / ZX 300 provides finance-grade wind measurements up to typical hub heights and have demonstrated consistently reliable and available wind measurements to ranges from ground level up to an IEC compliant met mast at the UK Remote Sensing Test Site.

All terrains

In October 2020 the Consortium for the Advancement of Remote Sensing (CFARS) released its literature review of Remote Sensing Devices operating in complex flow. These devices included the WindCube (Leosphere, a Vaisala company), Triton Sonic Wind Profiler (Vaisala) and ZX 300 (ZX Lidars), a Continuous Wave Lidar.

Ground-based Lidars and Sodars employ a variety of beam probing or scan patterns by which the horizontal wind speed, vertical wind speed and wind direction are derived - all assume homogeneous flow conditions within the scan / beam volume. In contrast, traditional meteorological masts equipped with cup anemometers provide a single measurement at the installation point of the sensor. In complex flow, often caused by terrain and fixed objects, the assumption of homogeneous flow conditions within the measurement volume introduces differences between Lidar and cup anemometer. In situations like this a flow conversion technique can be applied.

CFARS compared the various techniques adopted when using a WindCube, Triton and ZX 300 remote sensor and presented the following analysis of the accuracy of each device pre- and post-conversion / correction of data to account for the complex flow as shown in Figure 4.

Across a broad range of cases previously published by ZX Lidars and Meteodyn incorporating 13 different wind project locations, data presented confirmed that CFD conversion of ZX 300 data in non-homogeneous flow conditions produced excellent agreement with collocated anemometry. As a result, the data can be considered as finance-grade in such situations.

ZX 300 performance in complex flow is achieved by its unique 50 Line of Sight measurements in just 1-second. From this baseline performance, the use of additional Complex Flow tools available from a range of service providers including WindSim,

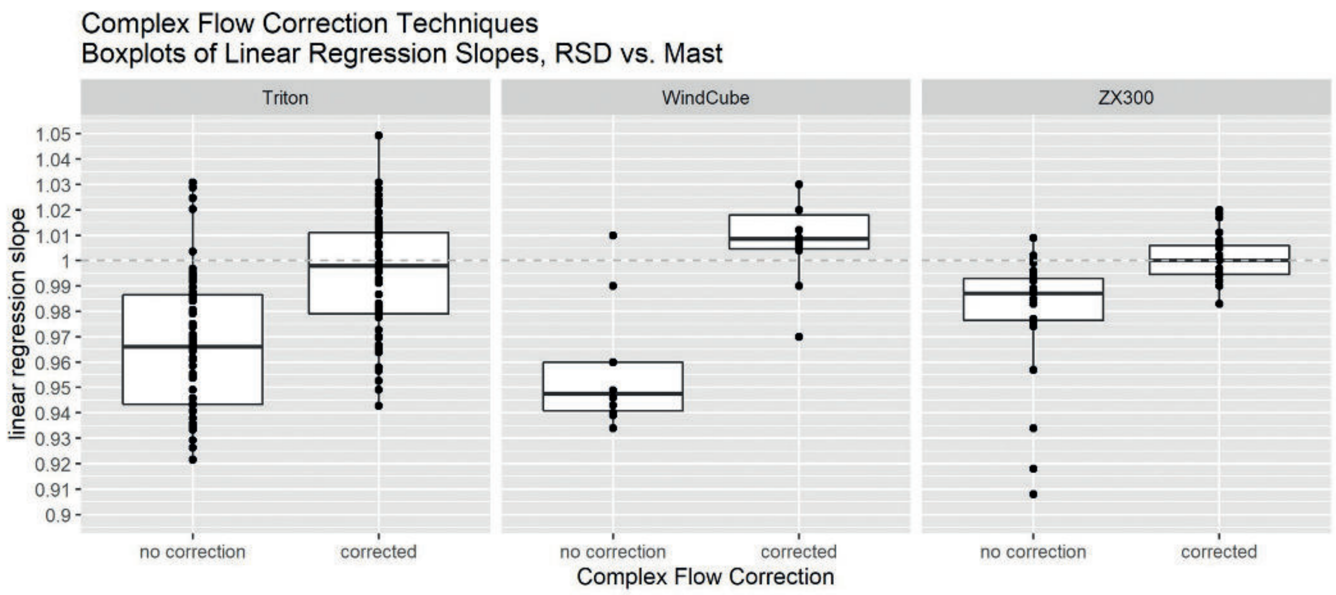


Figure 4: Presented at AWEA Wind Resource Assessment 2020. Courtesy of CFARS, A. Black, M. Debnath, A. Lammers, P. Mazoyer, R. Schultz, T. Spaulding, S. Wylie

Meteodyn and Natural Power are able to optimize the performance of ZX 300 further, delivering results that are traceable and auditable with a published conversion process.

With regards to the range of terrain classes as defined by Bingöl et al., 2009[1]. ZX 300 was also shown to perform to high levels of accuracy in all conditions including even highly complex sites as shown in Figure 5.

Continuing collaboration around this challenge has concluded in the successful development and validation programme by computational wind engineering company ZephyScience and independent wind consultancy Deutsche WindGuard of a further data conversion technique 'ZX CFR' (Complex Flow Resolver). This has now also demonstrated results to known and acceptable uncertainties allowing ZX Lidar systems to be deployed standalone in complex terrain and deliver wind speed and wind direction measurements that can be included within Energy Yield Assessments (EYAs) and Site Suitability Assessments (SA).

These CW Lidar feature extend further with horizontal profiling use cases as discussed below.

All rotors

Mounted horizontally, for example on wind turbines, Continuous Wave Lidars utilise the rapid data rate, which use a default integration time of 20.48 milliseconds giving a nearly 50 Hz data rate, to interrogate the wind field over a wide area in real-time.

In October 2020, Siemens Gamesa Renewable Energy (SGRE) released a

1 F. Bingöl Complex Terrain and Wind Lidars. Risø-PhD-52 (EN) August 2009

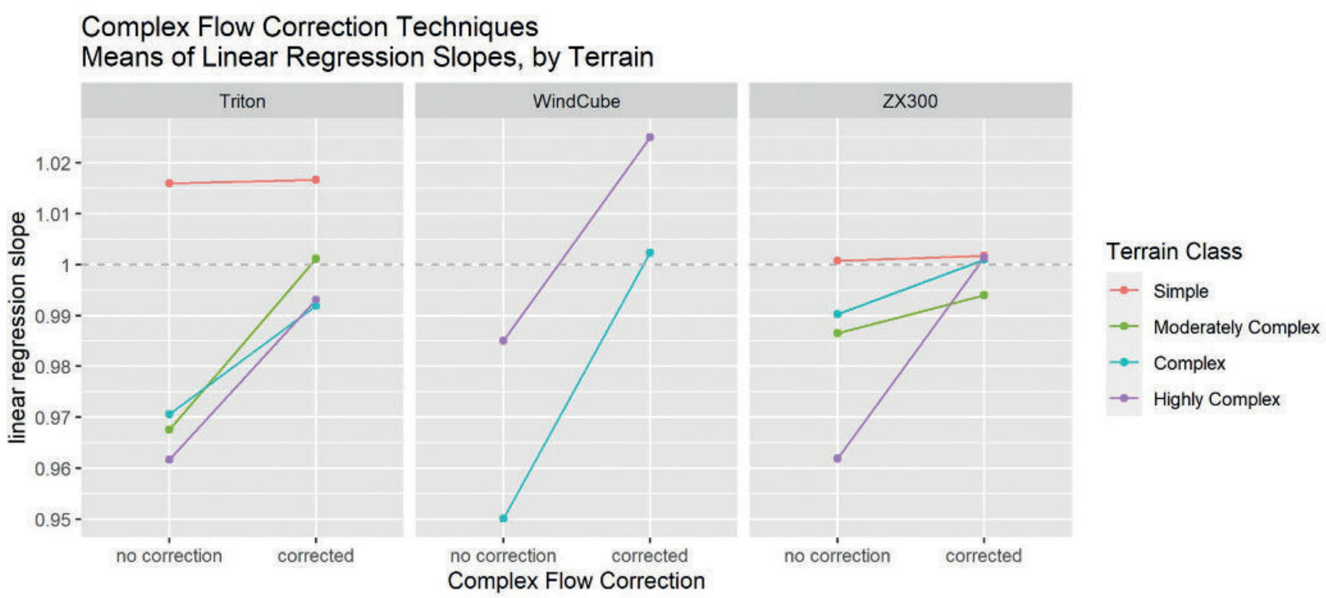


Figure 5: Presented at AWEA Wind Resource Assessment 2020. Courtesy of CFARS, A. Black, M. Debnath, A. Lammers, P. Mazoyer, R. Schultz, T. Spaulding, S. Wylie

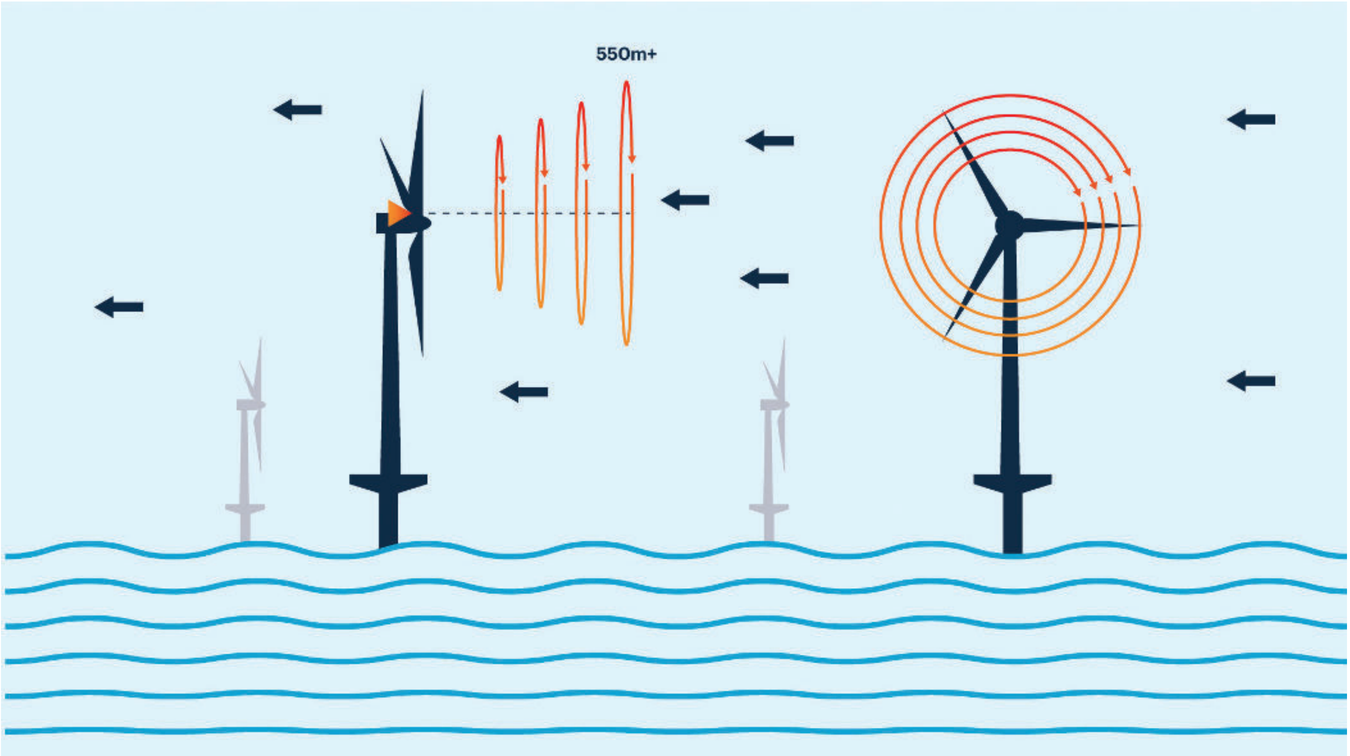


Figure 6: ZX TM measuring across the full rotor of large offshore turbine rotors and out to 2.5D

statement of testing and approval of nacelle-based CW wind Lidar 'ZX TM' for the purpose of Power Performance Testing on Siemens Gamesa wind turbines. This specific Lidar allows the power curve of SGRE wind turbines to be measured and verified as a function of the Hub Height wind speed and may be, when agreed with the customer, used instead of the procedure described in the IEC61400-12-1:2017 (ed. 1/ed. 2) using a meteorological mast and anemometry installation. This advance opens the door to significant cost reductions in fully-approved turbine power performance testing.

Importantly and drawing on the CW benefits, operational rotor equivalent power curves can also be measured with ZX TM's unique 50 points around the full rotor swept area, particularly important for turbines with larger rotor diameters offshore and on sites with complex veer or shear profiles onshore.

Finally, the rapid data of rate of ZX TM further permits investigation of turbulence in fluctuating flows at a sample rate approaching that of a sonic anemometer.

Conclusion

Continuous Wave Lidar has now been used for nearly two decades to analyse real-world issues in the wind industry. Over this period, experience has been gained in many applications and the general understanding of Lidars' capability has improved. It has now become a mainstream technique, and there is a much greater appreciation of the value it can offer to wind power and meteorological projects as demonstrated here. The decision for ZX Lidars to adopt CW technology for wind Lidar many decades ago continues to deliver benefits today and the wealth of data collected only allows for further optimisation to specific use cases, or adoption within new use cases.

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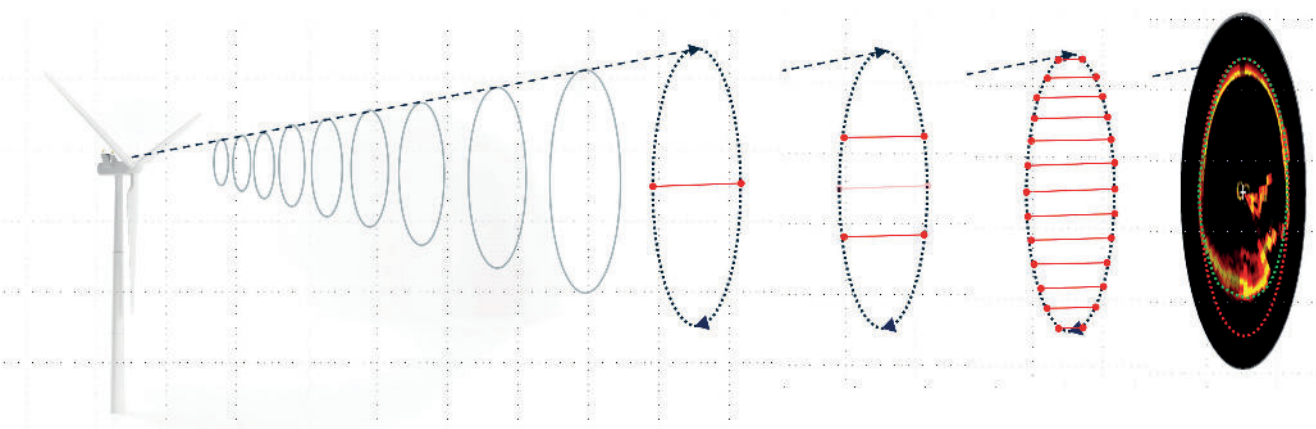

Figure 7: ZX TM measuring operational rotor equivalent power curves, increasing wind field knowledge when compared to traditional 2 and 4 beam modes