PO.011

A review of data uncertainty of floating lidars enabling use in analysis of operational wind farms

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Abstract

Floating LiDAR Systems (FLS) as a wind resource assessment tool has seen increasing market acceptance in recent years with multiple commercial deployments and new applications such as power performance testing, as an onsite weather station to feed into operational decision-making tools such as weather forecasting and wind farm fatigue forecasting. While systems have demonstrated performance to the accuracy standards laid out in various industry documents, the offshore wind industry is now requiring a greater understanding of the levels of uncertainty in floating LiDAR measurements. Greater coherence across this topic will benefit the industry by providing banks and other finance providers with a more accurate basis for the assessment of FLS derived P50s and P90s, leading to better rate pricing of risk and supporting a reduction in the cost of offshore wind finance through to operational phases.

Objectives & Methods

Research Objectives:

- Review data from studies conducted on FLS uncertainty and summarize advances
- Compare our own operating experiences to the uncertainty reduction path laid out by IEC and Carbon Trust
- Outline future research paths to improve market understanding of uncertainty in measurement from FLS

Review: Understanding Uncertainty with FLS

There is growing understanding of the value of FLS for advancing the industry. Both for economics and flexibility. But the uncertainty measure, which impacts the cost of financing, has not been fully vetted and evolved as the industry advances.

Carbon Trust Offshore Wind Accelerator (CTOWA) roadmap released in 2013 outlined a path commercial acceptance (Phases 1 – 3) and for uncertainty reduction for FLS[1]. Uncertainty for Floating LiDAR wind data was set at 4 – 7%, elevated over conventional fixed offshore met mast campaign that sit at 2.5%. This increased uncertainty reflected the the lack of a substantial body of validation evidence for early FLS and the potential operation of the systems in conditions outside of the validation envelope. As part of working to define performance for FLS that would meet campaign objectives, CTOWA developed the Key Performance Indicators (KPIs) in Table 1 that have been used to guide validation and measurement campaign performance evaluation. This approach to uncertainty focuses On linear regressions around wind speed and wind direction, and then further evaluates overall availability of the system.

Table 1: Carbon Trust Key Performance Indicators

Definition	Acceptance Criteria	
	Best Practice	Minimum
Mean Wind Speed – Slope	0.98 – 1.02	0.97 – 1.03
Mean Wind Speed – Coefficient of Determination (R-squared)	> 0.98	> 0.97
Mean Wind Direction - Slope	0.97 – 1.03	0.95 – 1.05
Mean Wind Direction - Offset	< 5º	< 10º
Mean Wind Direction – Coefficient of Determination (R-squared)	> 0.97	> 0.95

The body of work around uncertainty and commercial advancement has been further developed by a number of larger public and more focused private studies – here's a notable few:

- Both IEA task 32 subtask 1.5 and CTOWA produced Recommended Practices for better design, operations and management to decrease uncertainty[1,2,] and IEC provided a revision to their standard to include Annex L for remote sensing[.3]
- EDF Study incorporated Annex L framework and demonstrated that uncertainty for FliDAR was consistently below 4%, illustrating that reference uncertainty was a large portion of the results[4]
- Norcowe OBLEX-F1 offshore measurement campaign that illustrated that systems that are properly designed can achieve KPIs even with extreme waves.[5]
- ECN Wind Energy Ring Analysis study of a Fugro floating LiDAR, static LiDAR and offshore meteorological mast that showed how uncertainty varied by reference point[6]
- NREL proposed a view of the impact of local sites on uncertainty as a dynamic function[9].

The industry does not have a consistent interpretation of IEC 641001 Annex L. But there is a growing awareness of the uncertainty components and their drivers (Table 2). In our own experiences, we've begun work with 3rd party certifiers to quantify this formula (Figure 1), apply it to our projects (Table 3) and to manage it.

Table 2: Categories of uncertainty and potential drivers

Categories	Example Uncertainty Drivers in Industry
Reference uncertainty	Bias in fixed LiDAR or metmast's cup anemometer, wind tunnel uncertainty, cup classification, mounting effects and data acquisition uncertainty
Mean deviation bin-wise deviation divided by cup wind speed	1st phase validation between Stationary LiDAR measurements and reference - LiDAR Design, instrument fault, instrument noise, pointing accuracy 2nd phase validation against Metmast – all above, plus buoy design/movement, vibrations, sea-state
Standard deviation of the deviation	FLS Validation Campaign Design - interfe Reference uncertainty
Standard deviation of FLD	Data availability across bins [STD of measurements / sqrt (#records)] / bin average cup wind speed
Non-homogenous flow uncertainty	Upper atmospheric conditions that non-stochastic variations in flow
Mounting effect uncertainty	Mounting of the anemometer on mast – e.g. tower shadows
Separation difference uncertainty	Distance from met mast / measurement height
System classification	Evidence of repeatable validations

Figure 1: Example Uncertainty Formula

$$u_{flidar} = \sqrt{\sigma_{ref}^2 + \Delta v^2 + \frac{\sigma_{flidar}^2}{N} + {u^2}_{mounting} + {u^2}_{separation}}$$

Table 3: FLiDAR Projects can perform well below the 4% uncertainty factor

Lower Bin (m/s)	Upper Bin (m/s)	u_{flidar}	Lower Bin (m/s)	Upper Bin (m/s)	u_{flidar}	Lower Bin (m/s)	Upper Bin (m/s)	u_{flidar}	Lower Bin (m/s)	Upper Bin (m/s)	u_{flidar}
4.25	4.75	3.44%	7.25	7.75	2.23%	10.25	10.75	2.01%	13.25	13.75	2.11%
4.75	5.25	3.69%	7.75	8.25	2.32%	10.75	11.25	2.07%	13.75	14.25	2.08%
5.25	5.75	3.01%	8.25	8.75	2.14%	11.25	11.75	2.05%	14.25	14.75	2.03%
5.75	6.25	2.79%	8.75	9.25	2.05%	11.75	12.25	2.11%	14.75	15.25	2.18%
6.25	6.75	2.22%	9.25	9.75	2.04%	12.25	12.75	2.04%	15.25	15.75	1.95%
6.75	7.25	2.42%	9.75	10.25	2.04%	12.75	13.25	2.00%	15.75	16.25	2.04%

Source: Detlef Stein, DNV-GL, Evaluating AXYS FliDAR Wind Sentinel data, March 2016

Results: Best Practices for Mitigating Uncertainty

AXYS commercializes its FliDAR WindSentinel (FLiDAR) and manages uncertainty in several ways:

Design of the System for Accuracy: FLiDARs are specifically designed to support LiDARs offshore and supply data accuracy comparable to a met mast. Buoy motion can be compensated in real time by correcting the wind raw data using motion sensor data captured on the buoy during assessment campaigns.

Design of the Validation Trial: FliDARs have passed every validation campaign with typical accuracy rates >0.98 R2 when compared with a met mast, across multiple theatres of operations in a variety of sea states. The FLiDAR is placed in proximity to the Met Mast and then are validated against the Met Mast and correlated to each other (See Figure 2 and Table 2 below). Each wind speed and direction data point is plotted against Metocean conditions (e.g. wave statistics) to ensure no systematic error or sensitivity in the data.

Table 2: Example of Recent AXYS FliDAR WindSentinel Validation Campaign Against Met Mast

	88m			68m			48m		
	r2	slope	offset	r2	slope	offset	r2	slope	offset
Unit 1	0.9825	1.0047	4.0577	0.9895	1.0264	4.0577	0.9895	1.0271	2.4223
Unit 2	0.9846	1.0029	3.4251	0.9889	1.0267	4.4378	0.9924	1.0262	1.8153
Unit 3	0.9800	1.0032	5.2399	0.9838	1.0256	5.6647	0.9871	1.0281	3.6889
Unit 4	0.9777	1.0039	4.0265	0.9823	1.0288	5.0286	0.9827	1.0272	2.2357

KPI-AC passed best practice | **KPI-AC passed minimum** | **KPI-AC failed**

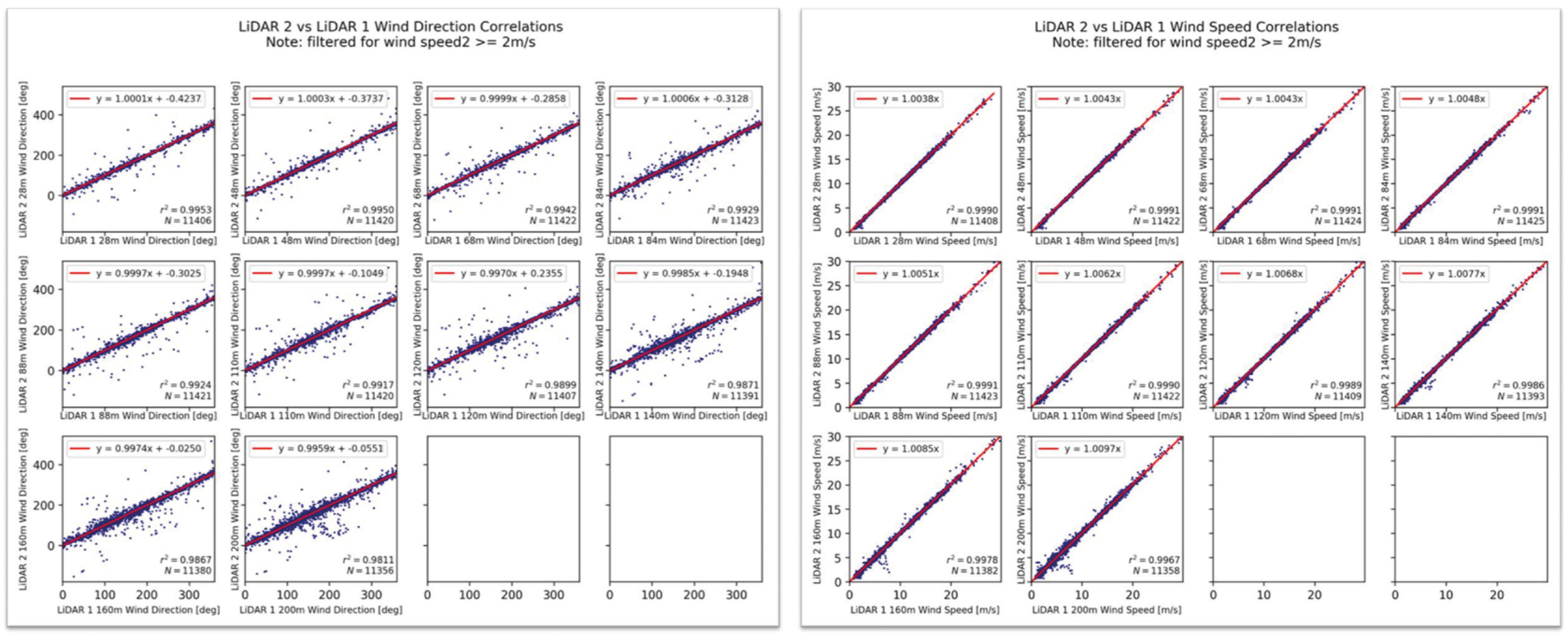

Figure 2: LiDAR to LiDAR Correlations

Deployment of the System: The LiDAR units and other Metocean sensors are sensitive instruments, calibrated and validated ahead of a measurement campaign. Care is taken in demobilizing, packaging and shipping post-validation. Recommissioning at the measurement site is done to revalidate data availability and reconfirm data quality ahead of the start of any campaign.

Operations of the System: Systems need to sustain a high level of data availability through extreme weather. AXYS FLiDARs are for long term deployments with hulls designed from decades of long-term survivability in hostile marine environments, backed by multiple redundant power supplies and fail-over telemetries. The buoys have availability rates of ≥96% - 99%, surviving multiple year campaigns in challenged waters where the significant wave height reached 5.9m and the waves nearly 11m. Systems are monitored continuously for overall health and Data Quality. Operations maintain the systems to reduce risks. Data quality checks include regular interval analysis to identify any inconsistent performance observed during the campaign, identifying and eliminating any root causes.

Conclusions & Future Directions

Advances have been made to move FLS along the commercialization cycle and reduce uncertainty, but the application of Climate Trust uncertainty and Annex L is applied in different ways depending on the engineer and their experiences, the particular project, and other factors. More collaboration is necessary in the industry to provide clear uncertainty figures and manage the cost of financing. That collaboration could include:

- The industry needs to agree upon a framework for the components of uncertainty and the metrics to evaluate them, including how Annex L should be applied consistently across projects.
- A revaluation of the FLS should assess the commercial classification of various participants in the industry and the accurate uncertainty of delivered data by system.
- Additional studies on sea state should be done to either confirm no impact, or identify the variations in impact across system classifications/design.
- More sharing of uncertainty data at an industry level would facilitate better understanding of potential systematic errors or sensitivity of wind speed and direction by system, reference type, other sources, etc.
- Research should identify a higher performing reference than a cup to eliminate/reduce reference uncertainty[4,5]

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