

Fraunhofer IWES Wind Lidar Buoy at an offshore measurement site in the German North Sea

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Turning motion into information: further advancing floating lidar turbulence measurements

Words: Warren Watson, Fraunhofer IWES and Julia Gottschall, University of Strathclyde

As floating lidar takes on the challenge of measuring offshore turbulence, researchers are finding new ways to turn platform motion into useful information. A novel processing method could reveal a more complete picture of atmospheric turbulence, and provide the industry with more accurate measurements.

The 2025 Offshore Wind Accelerator (OWA) Roadmap [1] extends the established maturity framework for floating lidar systems (FLS) to include turbulence intensity (TI). The Fraunhofer IWES Wind Lidar Buoy has become the first FLS to achieve Stage 3+ under this framework.

While this milestone concerns the demonstrated performance of the complete measurement system, research into new processing methods is also expanding the turbulence information that floating lidar can provide.

From wind resource to a more complete site assessment

Over the past decade, floating lidar systems have changed offshore wind resource assessment. Rather than constructing an expensive fixed offshore meteorological mast, wind farm developers can install a vertically profiling lidar on an autonomous floating platform and deploy it at a prospective wind farm site.

Fraunhofer IWES has accompanied this development since its early stages. A first prototype of the Fraunhofer IWES Wind Lidar Buoy was tested alongside the FINO1 offshore meteorological mast in the German North Sea in 2013, and the technology has since been used in commercial and research campaigns in Germany and internationally.

The next challenge is more demanding. For many offshore applications, mean wind speed alone is not sufficient. Turbulence intensity describes fluctuations around the mean and is relevant to turbine loading and structural design. Obtaining reliable turbulence measurements from a moving platform, however, is more difficult than measuring mean wind speed.

A new '+' in the OWA Roadmap

Since 2013, the Carbon Trust's Offshore Wind Accelerator Roadmap [1] has provided a common framework for assessing the commercial maturity of floating lidar systems. Stage 1 establishes an initial performance basis, Stage 2 represents the pre-commercial phase and Stage 3 indicates commercial maturity against the roadmap's criteria.

Stages 2+ and 3+ also assess a system's capability to measure turbulence intensity. The '+' does not prescribe a particular motion compensation method or processing algorithm. Instead, the framework considers demonstrated measurement performance using the algorithm selected by the system provider.

This leaves room for different technical approaches, provided that the resulting TI performance can be demonstrated against the requirements of the intended application.

The first Stage 3+ system

The Fraunhofer IWES Wind Lidar Buoy has been confirmed to be the first FLS to achieve Stage 3+ under the latest OWA Roadmap. Its processing chain includes deterministic motion compensation, which provides a physics-based foundation for TI measurements [3]. This approach uses measured platform motion to account for its influence on lidar observations.

For some applications, statistical quantities such as Q90 trends or other percentile-based metrics are most relevant. For others, the quality of the individual ten-minute values and their agreement with a reference time series matter more. A processing method can therefore improve one aspect of TI performance without necessarily improving another.

Beyond a single TI metric

The underlying challenge begins with the motion of the floating platform. For mean wind speed, the effect of buoy motion can largely average out over a ten-minute interval. TI is different. Because it is derived from fluctuations around the mean wind speed, platform motion itself can appear as an additional fluctuation and distort the measurement.

Once this motion influence has been accounted for, further processing can focus on the quantity of interest. For conventional TI, this may mean improving particular statistical characteristics of the measurement. For a more complete description of turbulence, however, the aim is to recover the underlying three-dimensional turbulence statistics. This is where N-Beam introduces a new concept [2].

What if the motion was useful?

A floating lidar moves, and that motion can introduce unwanted effects into the measurements. The N-Beam method considers a different possibility: if the platform motion is known accurately, can it provide additional information about atmospheric turbulence?

A typical pulsed profiling lidar uses a fixed sequence of beams, with a five-beam configuration considered in this example. On a stationary platform, those beams repeat essentially the same orientations scan after scan. On a buoy, however, pitch, roll and yaw continually change the exact orientation of each lidar beam relative to the atmosphere. Over a ten-minute period, the lidar therefore observes not only five fixed beam directions, but a much larger number of distinct beam orientations, represented by N, the number of discretised beam orientations.

N-Beam uses the line-of-sight (LoS) statistics from these changing beam orientations to recover the components of the Reynolds stress tensor. The tensor describes three-dimensional turbulent fluctuations and contains six independent components. From its variance components, TI can be derived, while the covariance components provide additional information on the structure of turbulence.

With only a small number of fixed beam orientations, resolving these quantities is difficult.

On a moving platform, however, hundreds or thousands of subtly different beam orientations can become available during the averaging interval. This creates an overdetermined system: many observations for a comparatively small number of unknown turbulence quantities.

A least-squares solution can then be used to retrieve those quantities. In simple terms, the buoy's motion creates additional viewing geometries, and N-Beam converts those geometries into information.

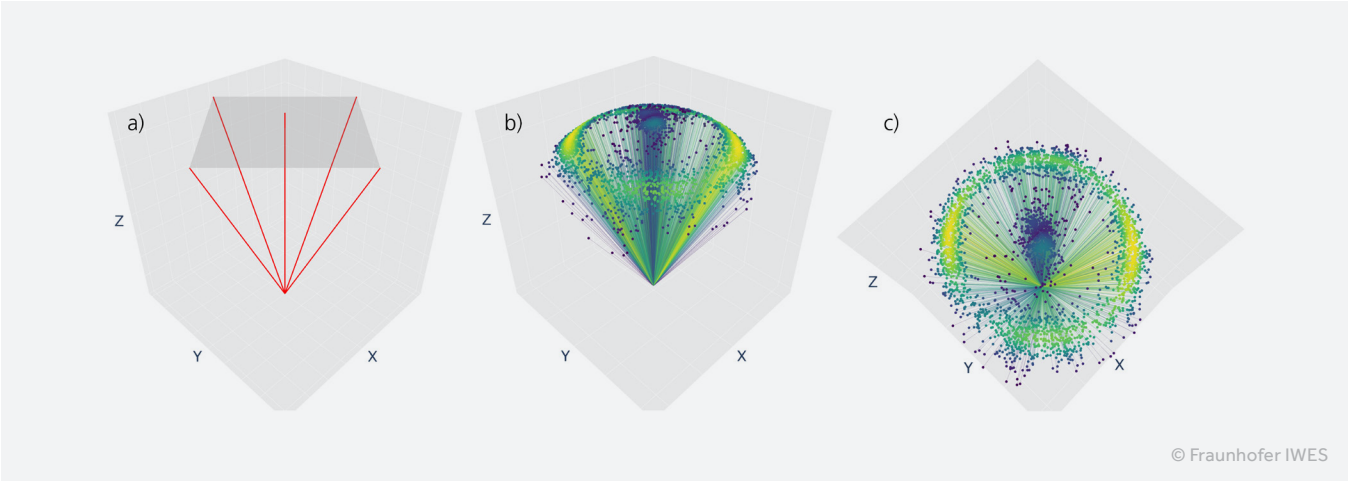
From five beams to N beams

Conventional velocity azimuth display (VAD) processing reconstructs wind-vector components from sequential beam measurements before deriving turbulence statistics from the resulting wind-speed time series.

For turbulence, that creates fundamental difficulties. The individual lidar beams are not measured at exactly the same time. Spatial averaging, measurement noise, residual motion and the time between beams can therefore influence the reconstructed fluctuations.

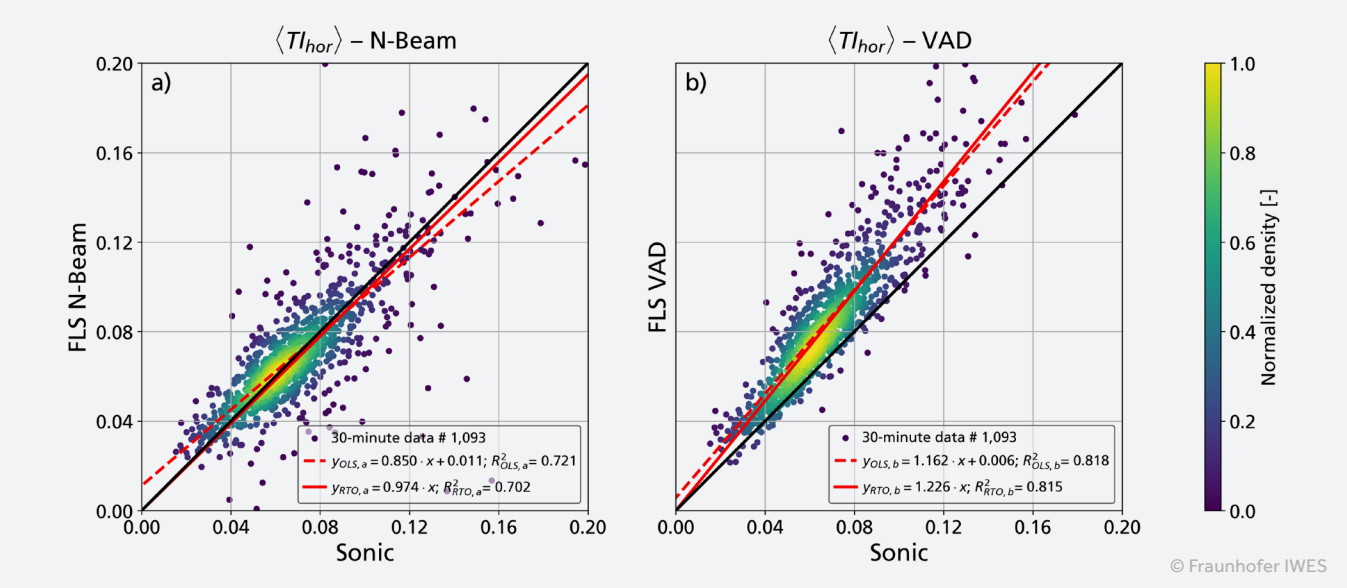
N-Beam uses a different approach. Rather than first reconstructing an instantaneous three-dimensional wind vector for every scan, it works directly with second-order LoS statistics over the averaging period. It then uses the available beam orientations to solve for the turbulence quantities. The large number of orientations provides additional information for the retrieval.

Importantly, N-Beam remains a physics-based method. The relationship between beam geometry, LoS statistics and the Reynolds stress components is explicitly defined, making the retrieval physically traceable.



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Beam geometry for a stationary five-beam pulsed lidar (a) and measured beam directions during a ten-minute period on a moving buoy (b and c) [2]



Comparison of horizontal turbulence intensity derived using N-Beam (left) and conventional VAD processing (right) against sonic anemometer measurements at 101 m on the FINO3 meteorological mast [2]

First offshore results

The method has been evaluated using measurements from a Fraunhofer IWES Wind Lidar Buoy deployed close to the FINO3 offshore meteorological mast in the German North Sea. A sonic anemometer mounted at a height of 101 m provided reference turbulence measurements. Further details of the measurement campaign and algorithm are provided in the published study [2].

The initial offshore measurements indicate improvements in turbulence intensity retrieval compared with conventional VAD processing. The chart above compares 1,093 sets of 30-minute measurements with the sonic anemometer reference at FINO3. The averaged horizontal turbulence intensity derived using N-Beam shows substantially less systematic overestimation than conventional VAD processing.

The two methods nevertheless differ in their regression and correlation characteristics, so the comparison should not be reduced to a single measure of accuracy.

Beyond improving TI estimates, N-Beam also enables the retrieval of additional three-dimensional turbulence metrics, extending the capabilities of conventional pulsed profiling lidars beyond scalar turbulence intensity measurements.

Some limitations remain. The retrieval of covariance terms is particularly challenging because sequentially scanning pulsed lidars do not measure all wind components simultaneously. Further validation across a wider range of atmospheric conditions, sea states, lidar configurations and floating platforms is also needed.

These findings indicate that N-Beam could improve TI measurements and additionally make three-dimensional turbulence statistics available from pulsed profiling lidars on moving platforms.

A portfolio rather than a single algorithm

N-Beam is one part of a broader processing portfolio, with the appropriate method depending on the required output. For conventional TI, Fraunhofer IWES has also investigated machine learning (ML) as an additional processing layer [4]. In the investigated case, ML primarily reduced systematic bias, while the scatter of the individual measurements changed only slightly.

This illustrates why the value of a correction depends on the metric being considered: an approach that improves a Q90 trend, for example, does not necessarily improve the individual ten-minute values to the same extent.

The two methods differ in how they produce their results. ML identifies relationships from training data, so its performance depends partly on how representative those data are. N-Beam derives turbulence quantities from a defined physical relationship between the beam geometry and the measured LoS statistics.

The two methods therefore address different needs rather than competing for the same task. ML can refine selected TI metrics, while N-Beam extends the FLS measurement capability towards three-dimensional turbulence characterisation.

The buoy is part of the measurement system

The latest evolution of the OWA Roadmap shows that expectations for floating lidar are expanding beyond conventional wind resource assessment. FLS are increasingly expected to provide not only reliable mean wind measurements, but also more detailed information about offshore turbulence.

The complete measurement chain matters. Lidar data, motion measurements, platform dynamics, timing and processing all affect the turbulence quantities that can be retrieved.

For the Fraunhofer IWES Wind Lidar Buoy, established processing methods provide conventional TI measurements, while approaches such as N-Beam offer the potential to retrieve additional three-dimensional turbulence quantities.

The buoy is therefore more than a platform carrying the lidar. Its movement becomes part of the measurement process, providing additional information about offshore turbulence.

iwes.fraunhofer.de/en.html

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