ZX Lidars

Wind speed at light speed

Using Wind Lidars in Complex Terrain

A Best Practice Guide

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Foreword

ZX Lidars is not a wind energy consultant and does not directly provide consultancy services, yet our position within the industry allows us to impart decades of common Best Practices which are shared in this document.

1 Introduction

Over the past decade, wind Lidars have transformed resource assessment for the wind energy industry, offering unprecedented flexibility, scalability, and measurement capabilities compared to conventional meteorological masts and cup anemometers. Unlike traditional point-based measurements, Lidars measure wind flow across a spatial volume, capturing what they *see*. Compared to a point-measurement, this volumetric approach is not incorrect; it is simply different. The industry's extensive reliance on several decades of mast-based data creates a need to align new measurement techniques with historical datasets.

In complex terrain, where wind flows are influenced by rugged topography, well-proven methods can be used to harmonise Lidar measurements with traditional approaches. This alignment is an opportunity to unlock the full potential of remote sensing devices like ground-based, vertical wind Lidar **ZX 300**, ensuring continued progress and innovation in wind energy development.

In doing so, Lidars provide a significant step forward in wind measurement technology:

- **Volumetric Measurement:** By scanning a conical area, Lidars capture wind dynamics at varying heights, offering a comprehensive picture of wind flow that is often more representative of what an eventual wind turbine will see, and therefore generate in terms of produced energy and electricity.
- **Portability and Scalability:** Easily deployable across challenging terrains, Lidars measure at turbine-relevant hub heights and future-proof data acquisition for evolving turbine designs.
- **Adaptability to Modern Wind Sites:** Lidars are particularly well suited for complex terrains, where traditional masts face logistical and economic challenges for any meaningful measurement at height.

This best practice guide from ZX Lidars describes how the perceived challenges of using remote sensing devices in complex terrain are overcome to unlock these wider benefits, using well-proven commercial solutions from leading authorities in the wind energy industry.

Figure 1: A typical ZX 300 Wind Lidar deployment in terrain that features complex flow characteristics

2 What is complex terrain?

Criteria for classing terrain as simple, that is for which site calibration is not necessary to perform a power performance test of a wind turbine, are given in clause 9 of the **IEC 61400-12-5**[1] standard. Clause 10 of this standard describes a method for assigning a class in the range 1-5 to terrain complexity based on terrain slope and ruggedness, with class 1 being simple terrain (passing the criteria in clause 9).

2.1 Terrain Characterisation

Key Parameters for Complex Terrain Classification include:

- **Slope**
  - Terrain with a significant gradient is considered complex. Steep slopes can induce flow curvature and vertical wind components, which impact wind measurements.
- **Standard Deviation of Elevation**
  - A measure of terrain variability within the area of interest. Large deviations in elevation indicate rugged, complex landscapes.
- **Terrain Ruggedness Index (RIX)**
  - The Terrain Ruggedness Index quantifies the proportion of the terrain that has a slope exceeding a specific threshold. RIX values are used to determine how much the terrain may disturb wind flow.
- **Ridge formations**
  - A step in terrain elevation, due to a formation such as a ridge, can cause significant flow distortion while still having a low RIX value. The presence of a ridge will lead to an increase in terrain class number.
- **Obstacles and Vegetation**
  - Additional features like forest canopies, buildings, neighbouring wind turbines, or other obstacles can significantly disturb wind flow. Guidance for defining a measurement sector undisturbed by such obstacles is given in clause 8 of IEC 61400-12-5.

2.2 Terrain Classes

The standard defines five levels of complexity based on these considerations:

- Class 1: “Simple” Terrain
  - Characterized by low slopes and relatively flat or rolling topography. Wind flow remains largely homogeneous, making it easier to measure and predict.
- Class 2-3: “Moderately Complex” Terrain
  - Terrain with more noticeable slopes and elevation changes. Unlikely to have significant flow separation. Flow deviations are moderate. Techniques such as Computational Fluid Dynamics (CFD) may be required to model flow conditions and establish the relationship between point measurements and volumetric measurements of wind speed.

[1] IEC 61400-12-5: 2022 - Wind energy generation systems, Power performance. Assessment of obstacles and terrain

- Class 4-5: “Complex” Terrain
  - Includes steep slopes, rugged topography, and large variations in elevation. These features cause significant flow curvature, vertical wind components, and turbulence. CFD is required to establish the relationship between point measurements and volumetric measurements of wind speed.

2.3 Why Terrain Classification Matters

IEC 61400-12-5 recognises that complex terrain introduces challenges for any wind resource assessments and power performance measurements. In these environments:

- **Non-homogeneous wind flow** breaks the assumptions of uniform wind conditions typically used in simpler terrain.
- **Measurement Bias** can arise between remote sensing devices and point-based measurements (e.g., cup anemometers), requiring corrections or flow modelling to maintain accuracy. This would be similar if two, fixed, point-based measurements were spatially separated i.e. if you were to compare two met masts installed a short distance away from each other in complex terrain.
- **Measurement representativeness** should be considered as complexity increases driving the need for more measurements across more complex sites.

Understanding the complexity of the terrain ensures that appropriate methods - such as site calibration, CFD-based conversions, or flow curvature recognition - are applied to produce reliable, finance-grade wind resource data.

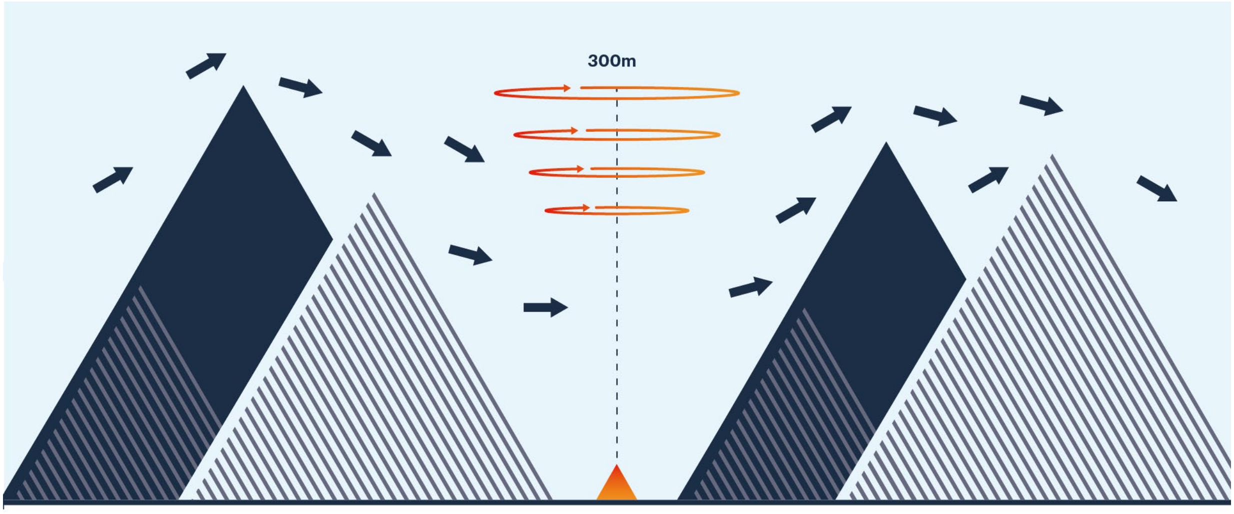

Figure 2: A simplified view of the changing wind conditions with terrain

3 Volumetric and Point-Based Wind Measurements

What does it all mean and why is this something to consider?

In complex terrain wind flow becomes inherently non-uniform. This complexity introduces spatial wind variations that Lidars *see* (and measure accurately) that are not seen by point-based instruments such as mast-mounted cup anemometers.

Bingöl et al. highlight the challenge of assuming homogeneity in rugged areas:

“Conically scanning Lidars assume the flow to be homogeneous in order to deduce the horizontal wind speed. However, in mountainous or complex terrain, this assumption is not valid, implying a risk that the lidar will derive an erroneous wind speed”.

Differences between measurement types can exceed 10% in such environments, particularly when vertical wind components dominate the flow, a phenomenon that cup anemometers themselves can fail to capture.

Differences in Measurement Scales are therefore simple to consider:

- **Lidars:** Measure wind flow across a circular scan area, naturally integrating flow variations.
- **Cup Anemometers:** Sample wind speed at a fixed, localised point.

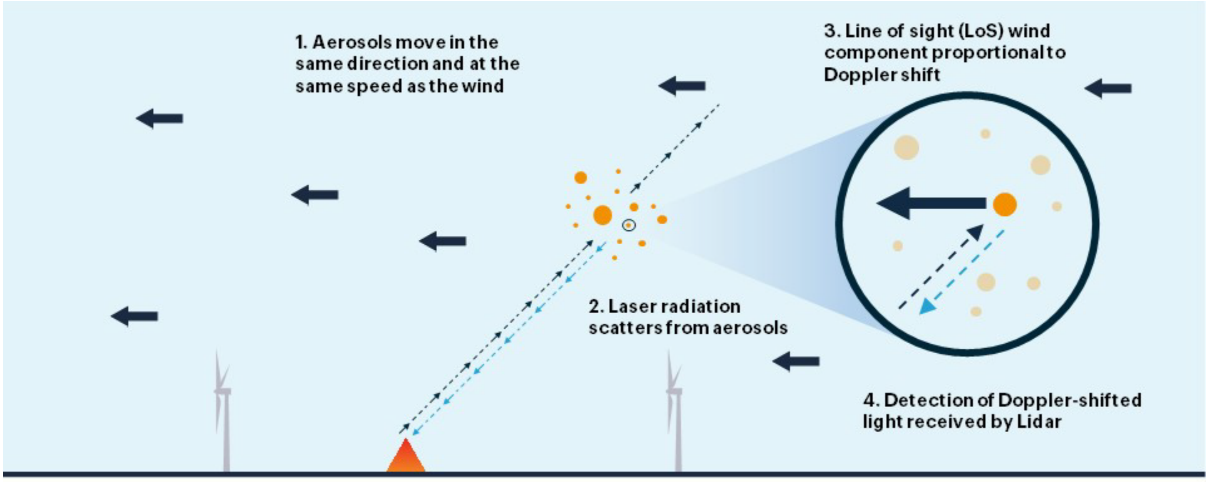

Figure 3: Wind Lidar Measurement Principles

3.1 How to convert Lidar measurements to look more closely like cup measurements in complex terrain

The industry’s shift from traditional point-based to volume-based wind measurements requires tailored solutions that preserve the integrity of both data sets while advancing industry standards. One such methodology is the use of Flow Model Conversions (or sometimes inaccurately referred to as Corrections). CFD models accurately simulate wind flow in complex terrains, offering a detailed understanding of the flow field. By solving the Reynolds-Averaged Navier-Stokes (RANS) equations, CFD models account for critical flow features such as wind inclinations, recirculation zones, flow separation, and terrain-induced turbulence. This approach allows for a high-resolution analysis of the wind field, incorporating both horizontal and vertical wind components that are critical in rugged terrain.

The CFD process involves creating a digital terrain model (DTM) based on site-specific orographic and roughness data, often sourced from high-resolution elevation datasets. The model grid is refined around areas of interest, such as the Lidar scan disk, to ensure accurate predictions of flow distortions and inclinations. Directional analyses are performed in small angular increments (e.g., 10° steps) to identify flow variations across different wind sectors. By comparing the modelled flow at Lidar scan positions to corresponding single-point reference locations, site-specific conversion factors are derived.

These conversion factors have been proven to translate volume Lidar measurements into equivalent point measurements that align closely with cup anemometer data at complex sites. This approach enables reliable and finance-grade resource assessments, even in complex terrains.

3.2 Lidars and Cups in Complex Terrain; why making them look similar is important

Lidars measure what they *see*, providing a richer, more comprehensive understanding of wind dynamics than single-point measurements. While industry reliance on mast-based data creates the need for alignment, this process is an opportunity to redefine measurement standards:

- **Accuracy in Complex Sites:** Lidars capture vertical wind components and flow variations often missed by masts.
- **Enhanced Site Assessments:** Post-processed Lidar data, corrected using CFD models, meets the stringent accuracy requirements needed for finance-grade assessments with a clear audit trail between pre- and post-processed data.
- **Future-Proof Measurements:** Lidar technology enables the industry to keep pace with increasing turbine hub heights and evolving site complexities.

4 Examples of Commercially Available Methodologies for Converting Wind Data

The need to relate volumetric Lidar data with traditional cup anemometer measurements in complex terrain has led to the development of several commercially available Computational Fluid Dynamics (CFD) solutions, often developed in collaboration with but independent of Lidar OEMs. These methods generate conversion factors that translate Lidar-derived wind speeds to point-based measurements, in support of bankable wind resource and energy yield assessments (EYAs) based on Lidar-only data. A non-exhaustive summary of these solutions is provided below.

4.1 Deutsche WindGuard's Complex Flow Solver (CFS)

Overview
Developed through collaboration between Deutsche WindGuard, ZephyScience, and ZX Lidars, the ZX Complex Flow Solver (CFS) uses high-resolution CFD modelling to resolve discrepancies between Lidar and cup anemometer measurements. This solution optimises Lidar data to account for terrain-induced wind flow distortions, producing converted results and uncertainties that can be used in the methodologies described in industry standards such as IEC 61400-12-1.

As detailed in Deutsche WindGuard's validation studies, ZX CFS applies the following methodology:

- **CFD Flow Simulation:** Using OpenFOAM, a validated CFD solver, a high-resolution terrain model is created based on orographic and roughness data. Mesh grids with resolutions as fine as 10 meters allow the model to simulate wind flow under various directional and turbulent conditions.

Conversion Factors: The CFD results generate direction-dependent conversion factors that transform Lidar's volumetric wind measurements into equivalent cup anemometer values.

Validation: ZX CFS results have been validated across multiple complex sites, demonstrating significant alignment improvements between Lidar and mast data.

Technical Detail
The ZX CFS approach employs a robust mesh generation process, where the terrain is discretised into high-resolution cells. Specific refinements focus on areas of interest, such as the Lidar measurement zone, to capture micro-scale flow variations caused by slopes, cliffs, and other topographic features.

Additionally, ZX CFS produces **Conversion Intensity Maps**, which identify optimal Lidar placement locations within a site to minimise terrain-induced measurement errors. As noted by Deutsche WindGuard:

"ZX CFS delivers direction-dependent conversion factors with known and acceptable uncertainties, providing the best available solution for bankable wind resource and EYAs in complex terrain".

Industry Perspective
Deutsche WindGuard, a recognised authority and bankable engineering consultant, positions ZX CFS as a solution that expands the usability of Lidar in challenging wind sites. Their work aligns with industry standards and reduces uncertainties to levels acceptable for EYAs and financing.

"ZX CFS results are subject 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)".

4.2 Meteodyn WT

Overview

Meteodyn WT, is a CFD-based solution designed to post-process Lidar data and compensate for flow distortions in complex terrain. Developed by Meteodyn, a specialist in wind resource assessment and flow modelling, this approach also uses the Reynolds-Averaged Navier-Stokes (RANS) equations to simulate site-specific wind flow conditions. The solution provides conversion factors that transform Lidar's volumetric wind measurements into values equivalent to those recorded by traditional cup anemometers.

Meteodyn WT has been validated across various terrain complexities, ranging from moderately complex hills to highly rugged mountainous landscapes with forest cover. As demonstrated by Sanquer and Woodward [1] (Sanquer and Woodward [1], 2016), applying CFD conversion factors significantly improves agreement between Lidar and mast measurements.

Technical Detail

Meteodyn WT's methodology follows a structured process to compute Lidar conversion factors:

- **High-Resolution Terrain Modelling:** Orographic and roughness data from sources like the Shuttle Radar Topography Mission (SRTM) and CORINE Land Cover databases are used to generate a site-specific digital terrain model (DTM).

Mesh Refinement: A fine mesh resolution (4 m vertically and 25 m horizontally) is applied across the entire site. At the Lidar location, the mesh is further refined to capture local wind flow variations precisely. This allows the CFD model to resolve speed-up and slow-down effects induced by the terrain.

Wind Flow Simulation: Meteodyn WT solves the RANS equations using a turbulence closure model (e.g., k-ε). Neutral stability is assumed for flow computation, and simulations are performed in 10° wind direction increments to produce a comprehensive wind flow profile across the site.

The resulting output is a **conversion factor rose**, which provides wind-direction-dependent conversion factors. These factors are applied to the Lidar measurements to adjust for flow distortions caused by terrain-induced recirculation, separation, and vertical inclinations.

Sanquer et al. emphasize the importance of this approach in addressing complex flow conditions:

"By using Meteodyn WT, the flow features associated with complex terrain, such as speed-up effects, vertical inclination, and flow recirculation, are resolved accurately, enabling Lidar data to be converted into bankable point-equivalent measurements".

4.3 DNV's Flow Curvature Correction (FCC)

Overview

DNV, widely regarded as a leading authority and trusted technical consultant in the wind energy industry, has developed the Flow Curvature Correction (FCC) [5] (DNV, 2024) service. This CFD-based solution corrects for flow curvature and terrain-induced complexities to align Lidar measurements with the point-based outputs of cup anemometers.

FCC employs DNV's proprietary CFD modelling approach to simulate site-specific wind flow conditions in challenging terrains. By accounting for deviations in flow caused by vertical wind inclination, recirculation zones, and non-homogeneous flow patterns, the FCC methodology produces correction factors that ensure accurate and finance-grade wind measurements from Lidars deployed in standalone configurations.

As DNV highlights:

"CFD-based Flow Curvature Corrections dramatically reduce differences between Lidar and Mast measurements, bringing uncertainties in line with traditional methods while maintaining Lidar's inherent flexibility".

Technical Detail

The FCC methodology involves the following steps to ensure accurate and validated Lidar post-processing:

- **High-Resolution CFD Simulation:**
  - DNV's approach uses CFD models to simulate wind flow fields based on site-specific orographic, roughness, and flow curvature data.
  - Terrain inputs, such as slope variations and vertical wind angles, are fed into the model to capture wind flow complexities, including updrafts and flow separations.

Wind Flow Correction Factors:

  - Flow Curvature Corrections are generated for multiple wind directions, typically in 10° increments. Each correction factor accounts for the deviation between the Lidar's volumetric scan and the expected horizontal wind speed at a fixed point, equivalent to a cup anemometer.

Site Optimisation for Lidar Deployment:

  - DNV also integrates FCC analysis into the site selection process to determine optimal Lidar deployment locations. By identifying positions with minimal flow curvature effects, uncertainties can be further reduced:
    "The higher the FCC correction, the higher the measurement uncertainty. By evaluating FCCs across a site, we can identify locations that minimize both Lidar uncertainty and wind flow modelling discrepancies".

Validation and Results Comparison:

  - Corrected Lidar time-series data are compared against cup anemometer measurements to validate the accuracy of the FCC methodology. Post-correction results show significant reductions in wind speed biases and uncertainty.

Industry Perspective

DNV's Flow Curvature Correction service has established itself as a critical tool for reducing Lidar measurement uncertainties in complex terrain. By leveraging CFD modelling to resolve terrain-induced flow complexities, FCC enables wind developers to adopt standalone Lidar solutions with confidence.

The FCC methodology not only enhances the credibility of Lidar measurements but also reinforces the broader industry shift toward cost-effective, flexible, and safe measurement solutions that eliminate the need for large, cumbersome meteorological masts.

4.4 WindSim, Flow Curvature Correction

Overview

WindSim [6] (WindSim [6], 2023) provides a CFD-based Flow Curvature Correction approach to align Lidar measurements with traditional cup anemometer data in complex terrain. WindSim's solution is designed to address flow variability induced by rugged topography, vegetation, and atmospheric effects, which can distort Lidar's volumetric measurements.

WindSim's approach integrates detailed terrain modelling and flow simulations to calculate direction-dependent correction factors. This ensures that Lidar data accurately represents wind speed measurements at specific points, reducing discrepancies observed in highly variable wind fields.

Technical Detail

The WindSim process incorporates:

- **Terrain and Flow Modelling:**
  - High-resolution digital terrain models (DTM) are developed based on site-specific elevation and roughness data.
  - The RANS equations are solved using WindSim's CFD solver to simulate complex flow conditions, including speed-up effects, vertical inclinations, and recirculation zones.

Correction Factor Generation:

- Correction factors are calculated for various wind directions, typically in 10° increments, to account for flow curvature and non-homogeneity in the Lidar scan area.
- Post-processing techniques ensure that volumetric Lidar data aligns with single-point cup measurements.

Validation and Use Cases:

- WindSim's FCC method has been successfully applied in multiple real-world projects, with results showing significant improvements in correlation between Lidar and mast data after correction.
- Sites in Greece, for example, demonstrated reduced residual biases following conversion with WindSim, improving confidence in the standalone use of Lidar.

4.5 Natural Power - Dynamics

Overview

Natural Power's Dynamics service offers an advanced CFD-based methodology to convert Lidar measurements for flow curvature in complex terrain. Their approach is specifically designed to reduce uncertainties associated with vertical wind inclinations, recirculation, and flow variability, ensuring that Lidar-derived data aligns closely with industry-standard point-based measurements.

As part of the CFARS Complex Flow Science Sub-Group, Natural Power has contributed to the validation and broader acceptance of CFD-based correction techniques for Remote Sensing Devices (RSDs).

Technical Detail
Natural Power's Dynamics approach includes:

- **Site-Specific Flow Modelling:**
  - High-resolution CFD simulations are conducted to capture complex flow features caused by terrain and vegetation.
  - Mesh refinements focus on the Lidar scan area to resolve small-scale flow variations.

Correction Factor Application:

- Post-processing algorithms apply direction-dependent correction factors to the Lidar data, reducing discrepancies caused by flow curvature and non-homogeneous wind fields.

Validation and Integration:

- Dynamics has been validated through multiple site deployments, showing consistent improvements in agreement between Lidar and mast data, particularly in forested moderately complex and highly complex terrain.

4.6 Ramboll, Flow Correction Factors

Overview

For projects in complex flow, Ramboll's CFD-derived heterogeneous flow correction factors can be utilised to incorporate standalone LiDAR data in both early-stage and finance-grade energy yield assessments, and site conditions assessments, with materially lower uncertainty than uncorrected data. Furthermore, the same process can be used to identify the optimal locations for proposed LiDAR devices on a site, ensuring flow heterogeneity is minimised as far as possible and a high-value measurement campaign is achieved.

Ramboll CFD is based on OpenFOAM[2], a powerful open-source CFD software package. The Ramboll CFD service has been fully developed in-house, and refined since 2013, and is specifically tailored to modelling wind farm sites, assessing wind flow across the full WTG rotor and all possible LiDAR measurement heights. Ramboll CFD is amongst the leading industry models when it comes to high horizontal resolution, ensuring that complex terrain features, and the resulting wind flow, are captured accurately.

Technical Detail

[2] OpenFOAM Foundation, https://openfoam.org/

Ramboll has developed a process for the derivation of heterogeneous flow correction factors using in-house Ramboll CFD, plus inputs from and the cooperation of LiDAR manufacturers, such as ZX Lidars. The following process is applied:

- High-resolution terrain, roughness and forest inputs, plus a high-quality and high-resolution mesh are vital to maximise the accuracy of a CFD simulation.
    - SnappyHexMesh is used to produce an unstructured mesh featuring higher vertical resolution close to the ground, where cells are only 1 m in height.
    - Horizontal mesh resolution of 11 m is used within the site area and is further refined in close proximity to forest and steep terrain, down to cell sizes of less than 5.6 m.
    - Forest is considered as a porous region within the mesh, based on the findings of Lopes da Costa[3].
- Directional simulations are undertaken, typically at 10° directional resolution for the purpose of heterogeneous flow correction factor derivation. The solver with a k-ε closure model is applied.
- 3-dimensional wind vector information is extracted from the CFD simulation results along the entire measurement track of the LiDAR at the measurement height under consideration, replicating the ZX Lidar's 50Hz sampling rate at that height.
- The modelled line of sight wind speed is then processed in the same way as the LiDAR measures, with a curve fit to the modulated sine-wave response, to replicate the wind vector measured by the LiDAR.
- This replicated LiDAR wind vector is then compared to the modelled point wind speed directly above the LiDAR device, in order to derive the flow heterogeneity correction factor.

Validation and use cases:

- Ramboll have performed multiple validations of the flow heterogeneity correction through comparisons to cup anemometry. These tests consistently improve all key LiDAR accuracy metrics at sites all around the world.
- Ramboll have taken part in third-party round-robin tests with co-located mast / LiDAR pairs, and accurately predicted absolute wind speeds, and flow separation at the sites.
- Ramboll have recently utilised heterogeneous flow correction factors in energy yield assessments for a range of use-cases, including complex and forested onshore wind farms in Australia and the UK, remote island-mounted LiDARs at offshore wind farms in Japan and Korea, and a LiDAR installed on a clifftop in Ireland.

Industry Perspective

Ramboll fully support the considered use of standalone LiDARs in measurements campaigns at onshore and offshore sites featuring complex flow. Prior to deployment in such, the use of high-resolution CFD modelling in order to identify the optimal measurement locations for LiDAR devices is strongly recommended, and where necessary, the implementation of heterogeneous flow correction factors should be used in order to make the most of LiDAR data, reducing prediction uncertainty and increasing project value.

[3] Lopes da Costa, J. – "Atmospheric flow over forested and non-forested complex terrain", PhD thesis – University of Porto, July 2007

5 Conversion Methodology Proof Book

CFD-based lidar conversion methodologies have been rigorously validated across a wide array of terrains and environmental conditions, showcasing their reliability and effectiveness for wind resource assessments. These approaches combine advanced computational modeling with precise lidar measurements, enabling developers to tackle the challenges of complex terrains with confidence. This section consolidates results from over 140 individual tests globally, demonstrating the robustness and adaptability of these methodologies.

5.1 Validation Scope and Applicability

Extensive validation efforts have tested CFD-based lidar conversion methodologies across a broad spectrum of terrains, environmental conditions, and project requirements. Key characteristics of these campaigns include:

- **Geographical Diversity:** Validations span a variety of geographic regions, including mountainous zones in Norway and Italy, coastal regions in Greece, and forested areas in the United Kingdom. This demonstrates the global applicability of these methodologies.
- **Complex Terrain Features:** Over 140 individual validations included steep slopes exceeding 10% ruggedness index (RIX), areas with significant flow separation zones, and terrains with mixed roughness lengths. These validations highlight the ability of these methodologies to address highly variable and challenging conditions.
- **Range of Conditions:** Campaigns encompassed a wide range of wind regimes, including low-speed environments, high-turbulence zones, and locations with pronounced seasonal variability. Key studies also addressed extreme weather conditions, further demonstrating the resilience of the methodologies.
- **Validation Benchmarks:** All results were benchmarked against traditional met mast measurements, providing a high degree of confidence in the accuracy and reliability of the converted lidar data. Average correlations between lidar and met mast data resulted in differences less than 1%.

5.2 Key Performance Metrics

The aggregated results from validation campaigns emphasize the precision and reliability of CFD-based lidar conversions in predicting wind speeds. Key findings include:

- **Strong Alignment with Met Mast Data:**
  - Across all campaigns, differences between converted lidar data and met mast measurements were reduced to below 1% in over 90% of test cases.
- **High Precision Across Diverse Conditions:**
  - Validation studies confirmed consistent performance across varying terrain complexities, wind regimes, and atmospheric conditions.
  - Specific campaigns showed reductions in mean wind speed errors from initial differences of 2.8% to converted values below 0.5%.
- **Proven Reduction in Systematic Bias:**
  - CFD conversions addressed terrain-induced flow distortions, reducing systematic biases and enhancing the representativeness of lidar data.

  - Standard deviations of wind speed errors were halved in validated campaigns, improving the consistency and quality of data for EYAs.

5.3 Conclusion of Validation Summary

The introduction and validation scope confirm the robustness and adaptability of CFD-based lidar conversion methodologies. Their demonstrated accuracy, particularly in aligning lidar data with met mast measurements, underlines their value as a cornerstone for reliable and finance-grade wind resource assessments. With over 140 validation campaigns globally, these approaches continue to set the standard for best practices in complex terrain applications, offering confidence and precision for modern wind energy development.

6 Managing Uncertainty in CFD Conversions for EYAs

EYAs are the cornerstone of wind energy project development, serving as the basis for financial decisions and operational planning. A critical aspect of any EYA is the management of uncertainty, which, if unchecked, can affect project bankability and stakeholder confidence. While Lidar technology has revolutionised wind measurement by providing more representative wind data, incorporating Computational Fluid Dynamics (CFD) corrections into the process also requires attention to uncertainty management.

The methodology outlined in the previous section demonstrates practically how Lidar, paired with established CFD practices, offers a reliable path to handling these challenges. Here, we discuss how following such methodologies impacts uncertainty and bias within the EYA process—and why it is essential to view this as a feature of diligent wind engineering, rather than a limitation.

6.1 Understanding Uncertainty in EYAs

Uncertainty in an EYA stems from several sources, including the variability in terrain, atmospheric conditions, and the inherent assumptions in modelling techniques. Managing these uncertainties is about quantifying and controlling them to deliver reliable, finance-grade data.

- The Role of Lidar and CFD:
  - Lidar provides volumetric measurements that reflect real-world turbine operating conditions better than traditional point-based systems. This data serves as the foundation for more accurate project development.
  - CFD conversions further enhance this data by addressing terrain-induced flow complexities. These conversions inherently introduce a level of uncertainty that then must be transparently managed.
- Industry Reliance on Managing Uncertainty:
  - The wind industry does not avoid uncertainty but instead builds frameworks to understand and manage it. Following established methodologies, such as those outlined by MEASNET, ensures that uncertainties are kept within acceptable ranges and are well-documented throughout the process.

6.2 The MEASNET Approach to Uncertainty Management

The MEASNET Site Assessment Procedure V2.0 provides a structured framework for handling uncertainty in remote sensing and CFD corrections. Annex C, Section C4 specifically addresses how uncertainties in CFD corrections should be calculated and communicated:

- Proportional Uncertainty Estimation:
  - According to MEASNET, the uncertainty associated with a CFD conversion is typically estimated as half the value of the conversion factor itself. For example, if a 4% conversion factor is applied, the associated uncertainty is 2%.
  - This proportional estimation provides a standardised and transparent method to account for the uncertainties introduced during the conversion process.

- Transparency in Reporting:
  - The MEASNET approach emphasizes maintaining transparency at every stage. By documenting assumptions, correction factors, and resulting uncertainties, developers can provide stakeholders with a clear understanding of how data is managed and interpreted.

Uncertainty is an inherent part of the EYA process, but it is one that the industry has learned to manage effectively. By following methodologies such as that outlined in this document, supported by frameworks such as MEASNET's proportional uncertainty estimation, developers can harness the full potential of lidar and CFD conversions. This approach not only minimises bias but also ensures that the data remains transparent, reliable, and finance-grade—all while reaffirming that the benefits of lidar-based assessments in complex terrains far exceed the challenges.

7 Advantages of ZX 300 in Complex Terrain

The performance of Remote Sensing Devices (RSDs), such as wind Lidars, can vary when deployed in complex terrain due to the potential impact of non-homogeneous flow fields. While conversion techniques such as CFD modelling provide tools to improve measurement accuracy, the ZX 300 was designed inherently and uniquely to be optimally suited for this environment. Its design and operational methodology allow it to deliver highly accurate, reliable, and bankable wind resource data in even the most challenging terrains.

7.1 Unique Features of ZX 300

- **High Temporal Sampling and High Resolution of Line of Sight (LoS) Measurements**
  - The ZX 300 operates at an industry-leading 50 Hz sampling rate, providing up to 50 independent Line of Sight (LoS) measurements every second.
  - This high temporal resolution allows for rapid and robust averaging, smoothing out localized variations caused by transient flow disturbances.
  - By capturing such a high density of wind velocity data in real time, the ZX 300 minimizes the impact of small-scale distortions and delivers consistent, reliable measurements, even in rugged terrain.
- **Resilient Measurement Process in Complex Flows**
  - The ZX 300 uses Continuous Wave (CW) Lidar technology, enabling it to focus its measurements at precise, fixed heights with high accuracy.
  - The system's advanced fitting algorithms leverage the full suite of LoS measurements to resolve wind vectors efficiently, capturing horizontal and vertical wind components while remaining resilient to complex flow conditions.
  - This ensures that wind speed and direction data remain accurate and consistent, providing a clear and representative picture of site-specific wind resource conditions.

7.2 Performance and Validation of ZX 300 in Complex Terrain

The ZX 300 has been rigorously tested and validated for use in complex terrain as part of independent industry studies. The CFARS Complex Flow Study [7] (CFARS, 2020) highlights its outstanding baseline performance and its ability to deliver finance-grade data with or without post-processing:

- Across a range of complex terrain classifications, ZX 300 demonstrated excellent agreement with collocated cup anemometers, achieving minimal bias and scatter without the need for significant conversion.
- When CFD conversions were applied, results achieved near-perfect alignment, with slope values reaching **1.001** and standard deviations reduced to as low as **0.010**.

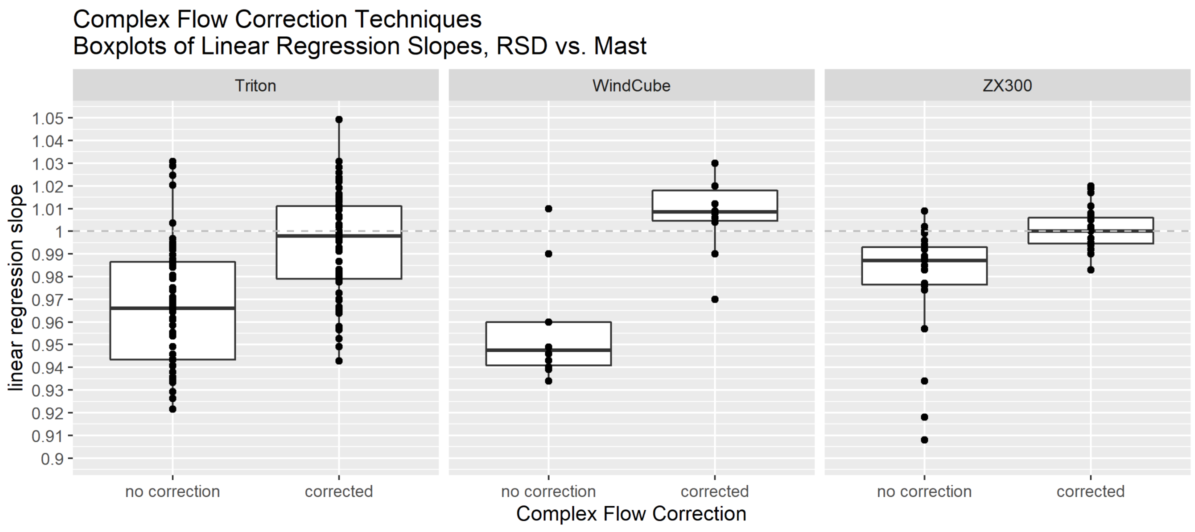

Figure 4: Presented at AWEA Wind Resource Assessment 2020. Courtesy of CFARS, A. Black, M. Debnath, A. Lammers, P. Mazoyer, R. Schultz, T. Spaulding, S. Wylie

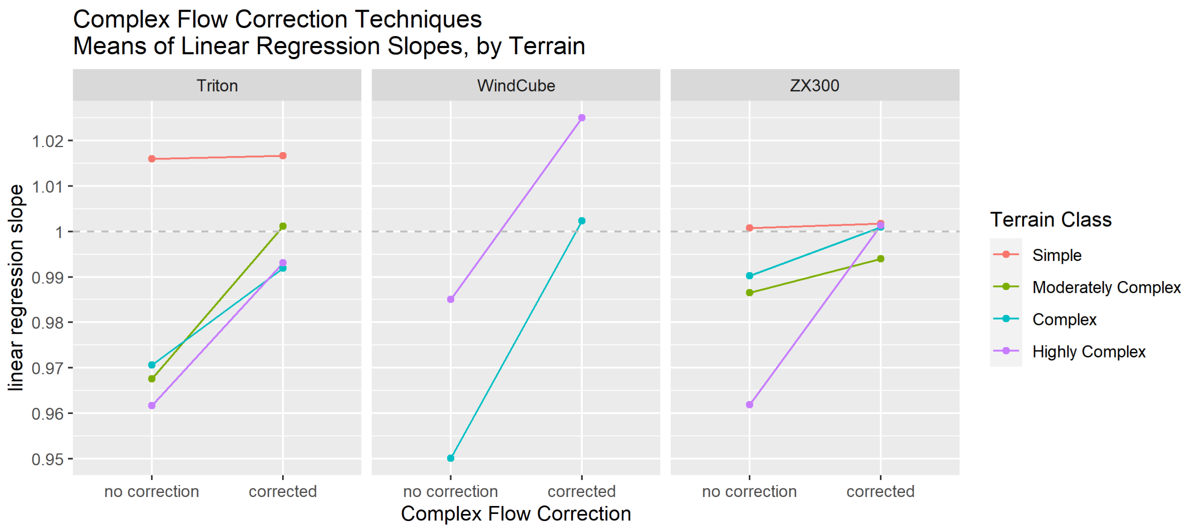

Figure 5: Presented at AWEA Wind Resource Assessment 2020. Courtesy of CFARS, A. Black, M. Debnath, A. Lammers, P. Mazoyer, R. Schultz, T. Spaulding, S. Wylie

As an aside, it is the same inherent system design features that has established ZX 300M - the marinised version of ZX 300 – as the industry standard Lidar offshore, accountable for more than an estimated 95% of all new wind measurements offshore. In this use case, the complex motion-induced bias of a floating platform is negated by ZX 300Ms rapid and resilient measurement principles effectively 'freezing' out the rapidly changing sea state induced motion encountered. ZX 300M is available on all commercially-available Floating Lidar Systems and has been extensively validated over two decades of operations offshore. It is unlikely that any new permanent met masts shall every be constructed offshore for wind project development due to the now proven and accepted performance of ZX 300M.

8 A flexible, thorough methodology for using wind Lidar in complex terrain

As this document illustrates, using wind Lidars in complex terrain demands a flexible yet rigorous approach that considers the unique challenges of these environments and applies one of the commercially available CFD-based solutions.

One such methodology is summarised below that may assist developers in achieving accurate, finance-grade wind resource assessments that can meet industry standards and maintain transparency at every stage. We are not wind energy consultants - we recommend the use of independent or in-house expertise to review and implement any such methodology.

8.1 Methodology and complex terrain checklist

- **Evaluate Terrain Before Deployment**
  a. Assess site-specific topographical features using tools such as terrain ruggedness indices (RIX) or slope analysis. Identify potential challenges like steep inclines, vegetation, and obstacles.
  b. Access / prepare / provide digital elevation models (DEMs) and high-resolution mapping to create a baseline understanding of the terrain.

Assess Overall Campaign Uncertainty

c. Beyond individual measurement uncertainty, evaluate cumulative uncertainties across the entire campaign. This includes lidar placement, terrain-induced flow effects, and CFD modelling accuracy.
d. Develop an uncertainty matrix that reflects site-specific factors and aligns with project risk tolerances.

Compare Multiple Measurement Locations within a site

e. Select and validate multiple potential lidar locations to ensure robust spatial coverage of the terrain utilising CFD conversions for each specific location.
f. Consider incorporating short-term roaming lidar campaigns to complement fixed-position data.

Validate Lidar Performance

g. Perform factory-based or mast validation for the lidar system to ensure it aligns with industry standards such as IEC 61400-12-1.

Deploy Lidar Systems

h. Install ZX 300 at multiple strategically chosen locations. Prioritise flexibility, allowing relocation based on initial results.

Apply Corrections and Analyse Results

i. Apply sector-based correction factors to wind speed data measured by Lidar.
j. Cross-check measurements from multiple locations or existing data sets to identify consistent patterns.

Maintain Transparency and Documentation

k. Document all assumptions, methods, and corrections applied during the campaign. Transparency ensures stakeholders understand how uncertainties were addressed and managed throughout the project.

9 Conclusions

The deployment of lidar technology in complex terrain assessments represents a significant advancement in addressing the unique challenges of non-homogeneous wind flows. By leveraging robust methodologies, such as integrating widely-available and validated CFD conversions with high-resolution lidar measurements, developers can achieve the precise, finance-grade data essential for modern wind energy projects.

Lidar systems like ZX 300, with their volumetric measurement capabilities and high temporal resolution, are uniquely suited to capture the dynamic wind behaviour inherent to complex terrains. The practical application of lidar, supported by CFD models, enables a deeper understanding of wind flow characteristics, including recirculation zones, flow separation, and turbulence. These insights are instrumental in optimising turbine placement, rotor size, and overall site performance.

Through the systematic application of CFD conversions, as outlined by frameworks like MEASNET, the industry has established effective approaches for managing and quantifying uncertainties. This ensures that lidar data not only aligns with traditional met mast benchmarks but also exceeds them in representativeness and scalability.

Practically, the adoption of these methodologies facilitates the expansion of wind energy into increasingly challenging environments. Developers can unlock previously inaccessible sites, optimise energy production, and achieve cost efficiencies by reducing the reliance on traditional, fixed-point measurement systems. Additionally, the transparency and repeatability of Lidar-CFD workflows ensure compliance with international standards, building trust across regulatory and financial landscapes.

As the industry continues to evolve, the role of Lidar technology and its integration with advanced modelling techniques will remain central to unlocking the full potential of wind energy. By embracing these tools and methodologies, developers can push the boundaries of what is possible, driving the sector toward greater innovation, efficiency, and sustainability.

10 Sharing and Evolving Best Practices: An Invitation for Feedback

The wind energy industry thrives on collaboration and continuous improvement, and this best practice guide is no exception. At ZX, we recognize the importance of collaborating and collecting expertise to address the evolving challenges of wind resource assessment, especially in complex terrains. This guide represents a culmination of industry knowledge and best practices, but it is only as strong as the contributions and insights from the wider wind energy community.

An Open Dialogue for Progress

While this guide provides one robust methodology for deploying lidar and integrating CFD conversions, we acknowledge that there is always room for refinement and further progress. As the industry grows and technology advances, so too must the frameworks and practices that support them. By sharing your experiences, insights, and questions, you can help shape the next iteration of this guide, ensuring it continues to reflect the very best practices.

We see this guide not as a static publication but as a living document. Future versions could include:

- Expanded case studies demonstrating real-world applications of lidar in diverse terrains.
- Updates to incorporate emerging standards or innovative technologies.
- Tools like checklists or decision matrices to make the methodologies even more actionable.

How to Contribute

We invite feedback from consultants, developers, financiers, and other stakeholders to ensure this guide remains relevant and impactful. Whether it's a suggestion for improvement, an observation from your own project, or a question about the methodologies described here, your input is invaluable. Together, we can continue to build a resource that supports transparency, collaboration, and excellence across the industry.

Thank you for being part of this shared journey. Let's advance wind energy assessments together.

11 List of abbreviations

CFARS: Consortium for the Advancement of Remote Sensing

CFD: Computational Fluid Dynamics

CFS: Complex Flow Solver

CW: Continuous Wave

DEM: Digital Elevation Model

DNV: Det Norske Veritas (a global quality assurance and risk management company)

DTM: Digital Terrain Model

EYA: Energy Yield Assessment

FCC: Flow Curvature Correction

IEC: International Electrotechnical Commission

LoS: Line of Sight

MEASNET: Measuring Network of Wind Energy Institutes

RANS: Reynolds-Averaged Navier-Stokes (equations)

RIX: Terrain Ruggedness Index

RSD: Remote Sensing Device

SRTM: Shuttle Radar Topography Mission

WT: Wind Turbine

ZX: ZX Lidars (specific to the ZX 300 Lidar system)

References

[1] Sanquer, S. and Woodward, A., 'Post-conversion of Lidar Data on Complex Terrains', WindEurope Summit, 2016.

[2] Deutsche WindGuard, 'ZX Complex Flow Solver for Lidar Corrections', Technical Report, 2021.

[3] Bingöl, F. et al., 'CFARS Survey of Correction Techniques for Remote Sensing Devices in Complex Flow', WRA 2020.

[4] Meteodyn, 'CFD Conversion of Lidar Data Using Meteodyn WT', White Paper, 2020.

[5] DNV, 'Flow Curvature Correction for Remote Sensing Devices', DNV Workshop, 2024.

[6] WindSim, 'Flow Curvature Correction for Lidars in Complex Terrain', WindSim Services Documentation, 2023.

[7] CFARS, 'Complex Flow Study for Remote Sensing Devices', Technical Report PR 131020, 2020.

ZX Lidars

About Us

In 2003 we released the first commercial wind lidar, pooling decades of fibre laser research from the science, security and energy industries. Designed specifically for the wind industry our Lidar has paved the way for many of the remote sensing devices seen in the market today. Our original lidar technology continues to innovate with world firsts such as taking measurements from a wind turbine spinner and being the first to deploy an offshore wind lidar, both fixed and floating. Our Lidars have also now amassed millions of hours of operation across 15,000+ deployments globally spanning two decades of commercial experience. Some of our proudest achievements are listed below; these are the earliest reported examples that we are aware of from open publications.

2003 - The first wind lidar to make upwind measurements from a turbine nacelle
2004 - The first and original commercially available lidar for the wind industry
2004 - The first wind lidar to investigate the behaviour of turbine wakes
2005 - The first wind lidar to be deployed offshore on a fixed platform
2007 - The first wind lidar to take measurements from a turbine spinner
2008 - The first wind lidar to be signed off against an industry-accepted validation process
2009 - The first wind lidar to be deployed offshore on a floating platform
2010 - The first wind lidar to re-finance and re-power a wind farm
2011 - The first wind lidar to be proven in a wind tunnel
2012 - The first wind lidar to be used with very short masts and secure project financing
2012 - The first wind lidar to be accredited for use with no or limited on-site anemometry for project financing by DNV GL
2014 - The largest batch of single-type lidar verifications against an IEC met mast
2015 - The first lidar designed specifically for offshore use, with the longest warranty available - 3 years as standard
2016 - The first wind lidar to support safe lifting on a jack-up vessel
2016 - The first wind lidar SCADA integrated on operational wind farms in replacement of site met masts
2017 - The first wind Lidar to be installed across a wind farm on a Lidar-per-turbine basis, uniquely mapping wakes across a wind farm
2018 - The first wind Lidar to satisfy all criteria for IEC Classification
2019 - The first wind Lidar to take wind measurements from a drone
2020 - The first wind Lidar to be accepted for bankable energy assessments in complex terrain standalone (without a met mast)
2021 - The first wind Lidar to attract more than £150bn+ of investment into wind energy projects
2022 - The first wind Lidar to be fully integrated into a retrofit wind turbine controller for Lidar Assisted Control
2023 - ZX Lidars moves to Willow End!
2024 - The first wind Lidar with a 5 year warranty and 5 year planned service interval as standard

Our Products & Services

ZX300

Onshore vertical profiling wind Lidar

ZX300M

Floating & platform-mounted vertical profiling wind Lidar

ZXTM

Turbine-mounted horizontal profiling wind Lidar

ZX Measurement Services

Wind Data as a Service