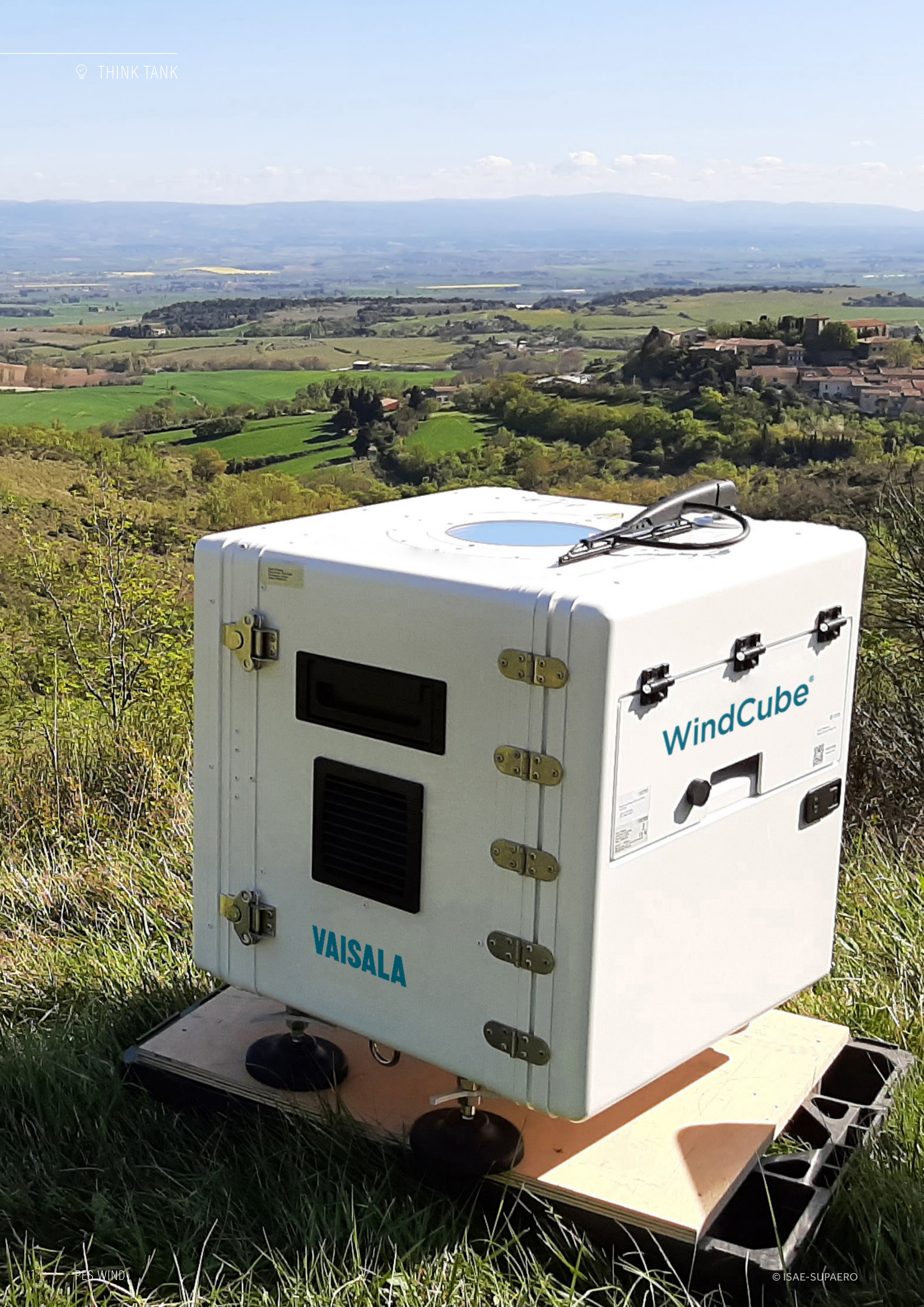
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WindCube vertical profiler in complex terrain

Lidar's impact on turbulence intensity and complex terrain

Lidar technology is transforming wind energy by providing accurate turbulence intensity and wind flow measurements in challenging terrains. As wind farms expand into complex and offshore environments, lidar's advanced capabilities offer crucial insights for optimizing turbine performance and ensuring efficient energy production.

2023 marked the best year ever for new wind energy capacity growth. Despite increased political and societal pressures paving the way for rapid growth, this new era of accelerated wind energy expansion reveals evolving challenges. Wind farm projects demand highly accurate wind measurements to ensure efficiency and reliability as the wind industry enters new frontiers, stretching into more complex terrains, offshore sites, and other challenging environments.

The ability to 'see' the wind's invisible characteristics enables project owners and operators to develop new wind farms and operate existing sites successfully. Yet two of the most significant challenges, measuring turbulence intensity (TI) and wind flow behavior in complex terrain, complicate decision making, as they still rely on traditional measurements from meteorological masts.

Thanks to innovative lidar, or light detection and ranging technology, the industry is progressing and providing wind behavior insights to address the challenges that TI and complex terrain pose.

How lidar works

Lidar technology operates by emitting laser pulses into the atmosphere and measuring the time it takes for the light to scatter back from particles in the air. Used to calculate wind speed and direction at various altitudes, lidar data provides a three dimensional view of wind behavior.

One significant advantage of lidar over traditional methods is measuring the wind at multiple heights and over expansive areas. Lidar's flexibility allows for more comprehensive and accurate wind assessments, especially in challenging environments.

With vast regions of easily developable flat terrain increasingly saturated, harnessing new wind resources requires venturing into more aerodynamically complex areas. At the same time, extracting maximum value from existing wind farms demands techniques like turbine level TI measurement for optimized operations.

By shining light on wind's unseen behavior in new and legacy wind farms, lidar empowers the wind industry to precisely measure, map, and mitigate the impact of turbulence intensity and complex flows in unprecedented ways.

WindCube vertical profiling lidar

The impact of turbulence intensity on wind farms

Turbulence intensity is the standard deviation divided by the mean wind speed value, quantifying the wind velocity fluctuations compared to the average wind speed. High TI can put incredible strain on turbine components through increased fatigue loading.

One of the most important wind related parameters, TI is widely used in many applications. Accurately measuring TI is vital for calculating turbine loading for design and certification purposes; micrositing turbine locations to avoid excessively turbulent areas; and understanding atmospheric conditions that impact turbine production.

Before lidar, measuring TI relied on met mast mounted anemometers and wind vanes. However, met masts are expensive, require permits, have limited measurement heights, and only provide point measurements without extrapolation.

Ground based and nacelle mounted lidars provide useful information and measurements to evaluate the accuracy of TI measurements. Scanning lidar instruments, particularly a dual scanning systems approach that uses intersecting laser beams, can measure TI across the entire rotor disk area. And nacelle mounted lidar provides an additional advantage with its direct line of sight orientation.

Several recent validation campaigns directly comparing scanning lidar measurements to met masts have confirmed their accuracy for TI. First, the NEDEL Offshore Wind Measurement Guidebook shows scanning lidar underestimated TI by less than 5% compared to a met mast during the Mutsu-Ogawara nearshore experiment. Measurements taken at the test site using 100 meter probe lengths found scanning lidar TI was less than 10% of the reference masts. Even using a longer 200 meter probe length, the lidar TI was within 15% of the mast data.

A recent white paper from Vaisala, the global leader in measurement instruments and intelligence for climate action, summarizes three validation campaigns where the company's WindCube Nacelle lidar, mounted on the turbine itself, evaluated TI measurement accuracy, with the global accuracy of the lidar TI hub height measurements exhibiting accuracy within 4.9% of the reference certified sensors.

These results show that modern scanning and nacelle-mounted lidars can provide TI measurements with accuracy that is on par with traditional anemometer methods. Understanding and accurately measuring TI is essential for better siting decisions, optimized turbine design, and more reliable energy production. However, as wind energy expands into more complex terrains and offshore environments, the industry faces additional challenges in accurately measuring wind flow, especially in complex terrain.

Overcoming complex flow challenges with FCR and CFD

Simple, flat terrain is becoming more difficult to permit, driving wind development to areas with more topographic complexity from hills, ridges, forests, and other obstacles. Complex terrain creates nonhomogeneous, horizontally varying wind patterns that are difficult to predict and measure using traditional methods.

With the wind deflecting over and around these environmental features, this breakdown in flow homogeneity can lead to errors in lidar measurements. For remote sensing devices in complex terrain, a site dependent correction is required to get precise and reliable wind speed data. Flow complexity recognition (FCR) and computational fluid dynamics (CFD) are the most accurate and historic correction methods.

FCR, integrated into the Vaisala WindCube vertical profiling lidar, accounts for the impact of moderate terrain complexity and provides a direct correction to the data. At some sites, however, FCR's simplifications reduce its accuracy. In these cases, full CFD software is the best post processing tool for managing more complex terrain induced lidar measurement errors.

Vaisala analyzes customers' prospective farms using a patent pending Terrain Complexity Estimation (TCE) tool, helping estimate possible complex flow lidar errors at the beginning of measurement campaigns and narrow in on the right correction method. By combining a neural network and wind reanalysis data to estimate WindCube wind speed biases at 100 meters above ground level throughout complex terrain sites, the TCE tool returns a terrain complexity map (.KML) that can be opened and viewed with Google Earth.

The TCE tool provides a map of estimated lidar errors. In most cases, the highest error will be where the wind potential is high, for example at the top of a ridge. To minimize the lidar error impact on the uncertainty, the best position will be in an area where no corrections are necessary, but these positions are rarely representative of the site's wind resource.

During a 2017 to 2020 project, the Fraunhofer Institute for Energy used scanning lidar to study wind flow in a small German wind farm in highly complex forested terrain. Researchers used just a single Vaisala WindCube Scan to perform specialized PPI sector scans to map horizontal winds across the site, using direct flow measurements with line of sight data to verify and calibrate numerical models.

Using this direct cross verification approach, Fraunhofer directly compared line of sight wind speed data from the PPI scans to CFD model data for the exact locations and geometries instead of reconstructing full wind vectors to mitigate uncertainty. As a result, the institute's team accurately characterized the wind flow behavior across the complex terrain, differentiated between multiple CFD models' performance, and fine tuned simulations to match the observed conditions.

This project demonstrated that even a single strategically deployed scanning lidar provides the comprehensive wind flow mapping required to successfully develop wind farms in highly complex terrain environments.

Dual scanning lidar for WRA in complex terrain

Using a carefully designed scan pattern strategy, scanning lidars can be redeployed to new locations every few months to build a comprehensive wind flow map. Decision makers can choose temporary locations to focus on areas exhibiting the most complexity from topographic features like ridgelines and slopes.

Dual scanning lidar does not experience the same kind of errors in complex terrain as vertical profiling lidar, due to the curvature of the flow across the different inclined beams. By employing two synchronized lidar scanners, this setup captures intricate topographical details with previously unheard of precision. This incredible accuracy allows for the creation of highly detailed 3D models of rugged mountainsides, dense forests, and winding canyons almost impossible to map without remote sensing technology. The flow characterization capabilities become even more powerful when utilized in more extensive campaigns with multiple coordinated scanning lidar devices.

The advantages of deploying dual scanning lidars at complex terrain sites include improved spatial extrapolation uncertainty, including validation of spatial extrapolation modeling and refinement of spatial modeling, and the ability to perform multiple measurements in remote and difficult to access areas. Benefits also include a simplified or no permitting process for installation, plus opportunities to measure turbulence and topography induced wakes for a better estimation of expected turbine operation time.

As the wind energy industry spreads into increasingly complex terrain with disparate wind behaviors, lidar's accuracy, flexibility, and mobility will only help it exceed the limitations of traditional anemometry.

Making the invisible visible

Whether used for turbulence intensity measurement, wind flow mapping in complex terrain, or any other wind characterization needs, lidar continues to advance rapidly. Capable of comprehensively measuring, mapping, and modeling the invisible characteristics of wind, lidar instruments unlock previously unheard of possibilities. These include developing wind farms in regions previously too complex for reliable wind measurement and extracting maximum value from operational assets through turbine level performance optimization. It may also be possible to open new frontiers for wind energy through unprecedented wind behavior mapping.

Wherever the wind blows, whatever invisible forces shape its currents and gusts, lidar innovation helps ensure nothing remains truly unseen. The wind's complex behaviors are finally coming to light, creating new opportunities for an industry harnessing that power to build a sustainable energy future.

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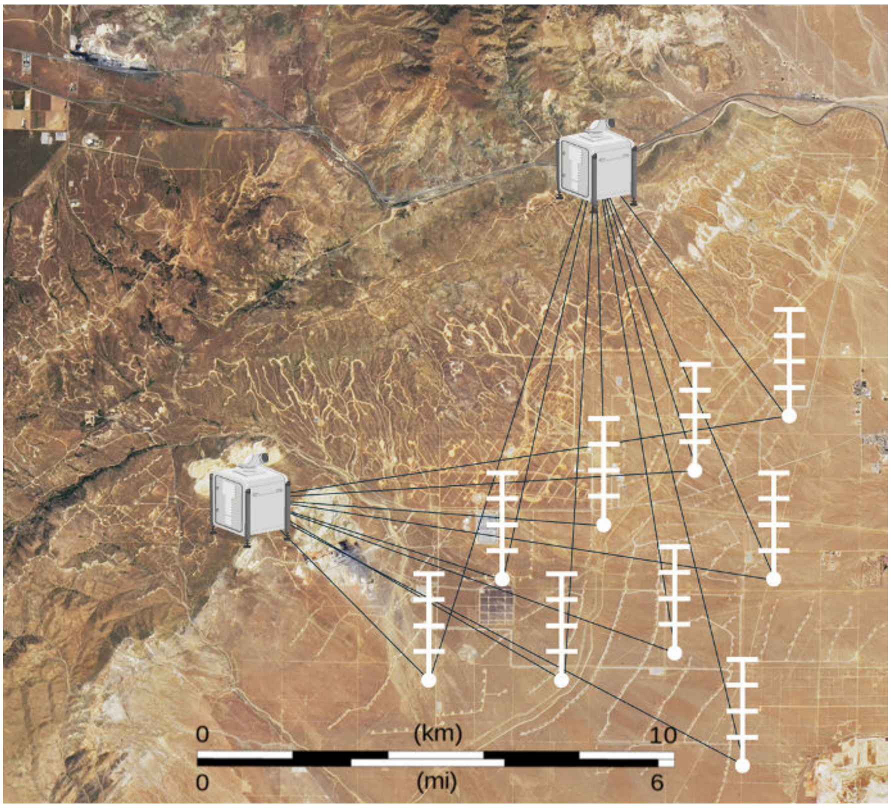

Dual scanning lidar in complex terrain

About the author

Julian Dajczgewand is the product offering manager for wind resource assessment (WRA) at Vaisala.

In this capacity, he drives the progression of product strategies tailored specifically for WRA applications.

Leveraging his technical expertise in optical hardware, Julian serves as primary technical support, guiding customers to comprehend the optimal utilization of lidars for their respective applications.

His role is instrumental in bridging the gap between complex technology and its practical application, ensuring customers can harness the full potential of Vaisala's offerings.