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Synchronized Agile Beam Scanning of Coherent Continuous-Wave Doppler Lidars for High-Resolution Wind Field Characterization

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Abstract: Developments of coherent continuous-wave lidar technologies for detailed studies of the three components of wind fields in the three-dimensional space has been pursued at DTU Wind Energy during the last decade with a concept called WindScanner. Since a single lidar only measures the wind component along the laser beam, the concept builds on synchronized agile beam-scanning of several lidars. The technological developments including synchronized double-prism-based scanning and an all-fiber in-phase and quadrature direction detection scheme are described. Several different instrument implementations have been realized and application examples from wind energy, structural design, aviation, boundary-layer meteorology, and recently also forestry and detailed studies in wind tunnels are highlighted. The wind lidar developments has not only proven to provide useful remote-sensing tools for wind field characterization at high spatial and temporal resolution but also holds prospects as tools for calibrating traditional point-monitoring anemometric devices which currently is investigated.

Keywords: Doppler wind lidar, Continuous-wave lidar, Synchronized multiple beam scanning, Double-prism scanner, WindScanner

1. Introduction

DTU Wind Energy has been leading the development of various scanning lidars utilizing the multiple-beam WindScanner concept which is about measuring the three wind components remotely by combining the line-of-sight speeds obtained from three steerable lidar beams crossing within the same volume [1]. One of the developments has been on mirror-based scanners for long-range pulsed lidars that in collaboration with the lidar manufacturer Leosphere has become an integral part of commercially available lidars. Another development has been on prism-based agile scanners for coherent continuous-wave lidars in collaboration with the lidar manufacturer ZephIR and this is the focus of this communication, which will review the technological developments including a synchronized double-prism-based scanning technology and an all-fiber in-phase and quadrature direction detection scheme. Several different instrument implementations have been realized and application examples from wind energy, structural design, aviation, boundary-layer meteorology, and recently also forestry and detailed studies in wind tunnels are highlighted.

2. Synchronized double-prism-based scanning for coherent detection of wind

The continuous-wave short-range WindScanner is originally building on the concepts of the ZephIR profiling lidar which scans the laser beam on a conical surface by rotating a single wedge-shaped prism. For agile scanning of the lidar laser beam, a double-prism scanner as depicted in Figure 1 has been developed which is similar to the classical Risley prism configuration but with the rotation axes of the two prisms not aligned but rather at the specific angle that allows the laser beam to pass through both prisms at the angle of minimum deviation in order to maintain a tight focus which is crucial for obtaining confined sampling volumes in the atmosphere. The position of the measurement location along the laser beam is obtained by a linear translation stage moving the light emitting and receiving fiber relative to the focusing lens in the transceiver telescope.

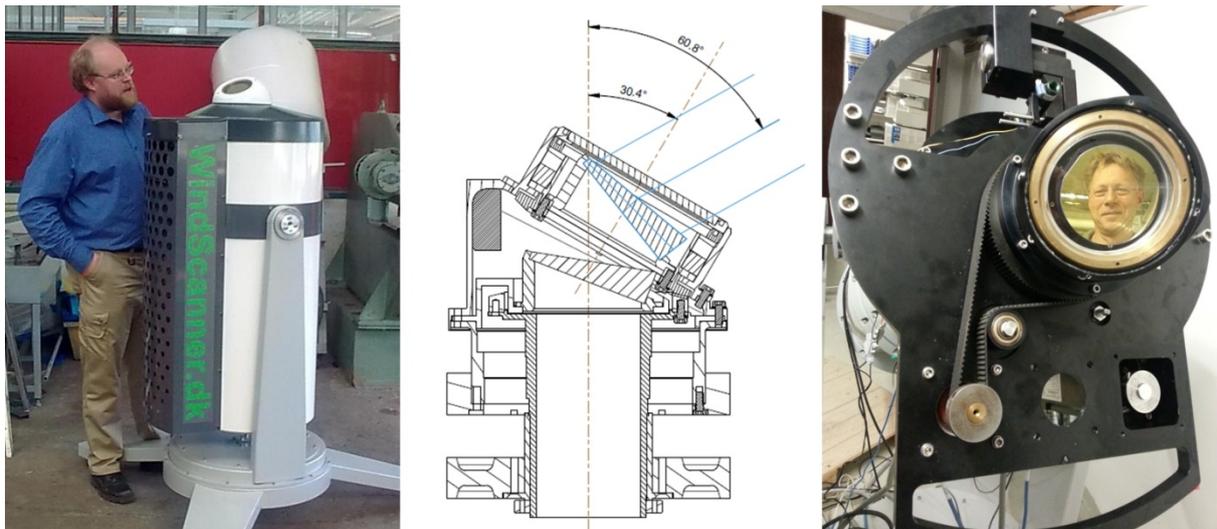


Figure 1. (Left) The exterior of the first generation short-range double-prism WindScanner. (Middle) The double-prism arrangement with individual prism rotation illustrated for the case of total maximum deviation of about 60° . (Right) The details of the scanner-head with one of the rubber belt transmissions visible.

The prisms are steered individually by one servomotor for each axis which allows the laser beam to be directed within a conical volume with a full opening angle of about 120° . All motors in all the lidars comprising the 3D WindScanner system are synchronously controlled by a Delta Tau Programmable Multi-Axis Controller system (PMAC) interconnected by optical fiber-based Motion And Control Ring Optical (MACRO) fieldbus technology. The focusing mechanism is driven by a linear motion motor and both stable ultrasonic piezo-ceramic motors and agile voice coil motors have been utilized.

A special rapid-scanning variety of the short-range WindScanner called a SpinnerLidar has also been created. The main difference is that it only has one single motor for driving both of the two prisms. The motor is operated at a constant but selectable rotation speed with a hardware-fixed gear ratio between the two prism axes such that a rosette-like scanning pattern can be completed within one second. The SpinnerLidar has not only been used from inside a wind turbine spinner but also from the top of wind turbine nacelles, either measuring the inflow or the wake [2].

Since the state-of-the-art wind turbines are becoming larger and larger, there is a drive for lidars that can measure at longer distances with small enough sampling volumes. Therefore, the WindScanner fauna recently has been populated by a new WindScanner creature using 6 inch optics instead of the 3 inch optics used in the original implementation.

During the course of the development, the coherent detection system has evolved from a heterodyne system where an acousto-optic modulator was used for shifting the zero Doppler frequency to about 27 MHz into a more robust homodyne system using an in-phase and quadrature detection scheme realized by an optical hybrid for achieving the direction sensing functionality [3].

3. Measurement application examples

Since the beginning of the WindScanner development in 2007 several measurement campaigns, as illustrated in Figure 2, have been performed. In one of the first campaigns one single WindScanner was used for studying the flow field over a steep escarpment of the westerly side of the Bolund peninsula in Roskilde Fjord in Denmark [4] and later a similar study was performed at a similar escarpment at the Prince Edward Island in Canada [5].

Two-dimensional synchronized measurements using two WindScanners with the scanning beams inside the measurement planes have subsequently been done for studying the downwash flow below rescue helicopters [6]. A similar approach has also been used for measuring inside wind tunnels [7] -

[8] as well as for studying the coherence of the inflow towards the Lysefjord bridge [9] where also the wake [10] of the bridge deck was investigated.

The main application field for the WindScanners is the field of wind energy and several campaigns for assessing both inflow to and wakes behind wind turbines have been performed using complete three-dimensional measurements from three synchronously sampling WindScanners. For instance, inflow towards a Vestas V27 horizontal axis turbine [11] as well as the wake behind a Nenuphar vertical axis turbine [12] have been measured by the short-range WindScanners and compared to models. Furthermore, the wake behind a wind break [13] and the wake behind a single Oak tree [14] have been studied by the WindScanners and the measurement capabilities in urban environments as illustrated in a recent overview paper [15] seems to be of interest to the architecture and pollution modeling communities.

The synergetic benefit of instrument complementarity regarding sampling volume and measurement distance was demonstrated in a field campaign where the large-scale flow over two mountain ridges was studied by pulsed long-range WindScanners and the local turbulent flow around a wind turbine located on one of the ridges was studied by continuous-wave short-range WindScanners [16]. Similar benefits on the very small scales inside a wind tunnel were achieved by combining a small easily handled Lidic telescope with the larger double-prism WindScanners [8].

Traditionally within the wind energy community mast-mounted in-situ point monitoring anemometers have been the standard measurement device against which wind lidars have had to be calibrated. However, currently DTU Wind Energy is attempting to reverse this situation by verifying the lidar Doppler speed estimation against a spinning wheel with a traceably calibrated speed [17] and then using the lidar for field calibration of cup and sonic anemometers [18]. This is possible by using continuous-wave lidars focused at short distances such that the sampling volumes become comparable or even smaller than the sampling volumes of the in-situ instruments.

The short-range WindScanner 2007 - 2017

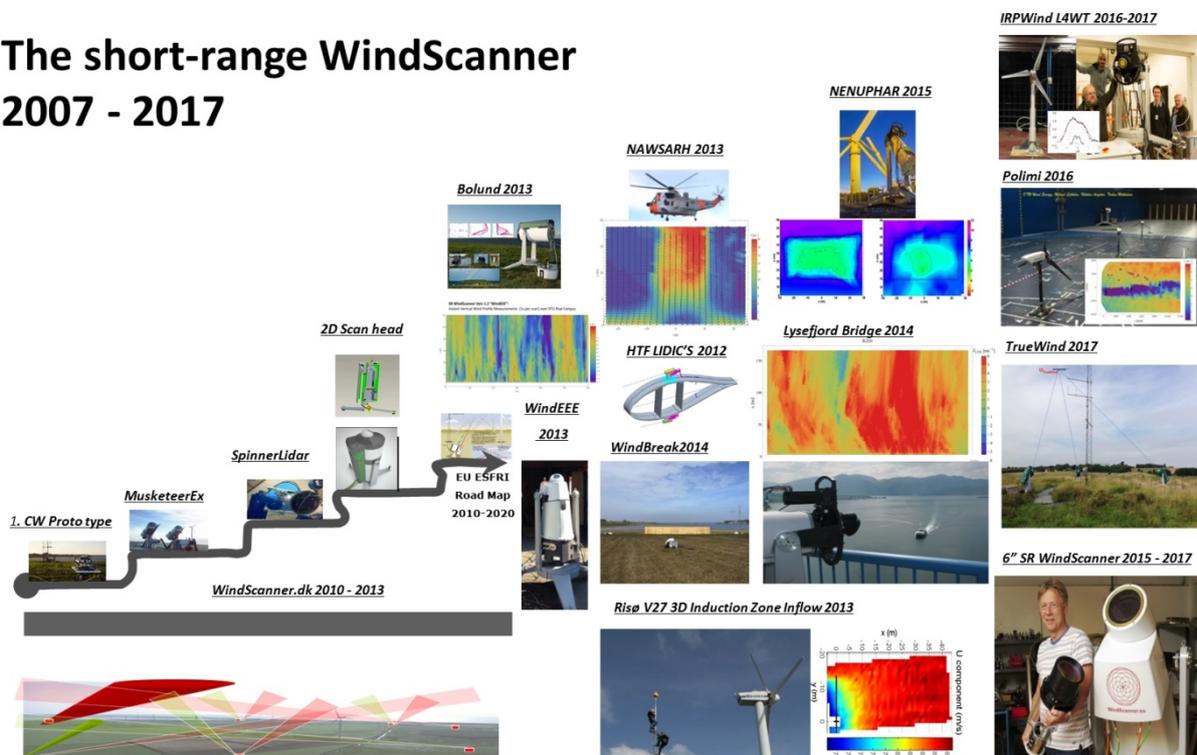


Figure 2. A flavor of activities with the DTU short-range WindScanners.

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