Low-cost semiconductor laser wind sensors (Billig halvlederlaser vindsensorer)

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I. Objective of the project

Our objective is to develop, demonstrate and validate prototype laser wind sensors that measure wind speed and direction based on low-cost, compact semiconductor lasers and new optical methods we have recently devised and patented. These wind sensor prototypes will represent the next-generation of compact, rugged and inexpensive laser-based wind sensors for wind energy research and turbine industry. The report on five project work packages (WP) is given in the following sections.

II. WP1: Project management and commercialization activities

The overall management of the project was headed by Jørgen Korsgaard Jensen, CTO and founder of Windar Photonics A/S – a spin-off company of OPDI Technologies A/S. Windar is dedicated to the commercialization of a patented lidar technology. Windar's strategy is to identify and pursue high-risk, high-gain commercial endeavours through purchase of technical services accomplished through collaboration contracts with the Technical University of Denmark (DTU). Last April 2012, Windar hired a new CEO in the person of Martin Rambusch. In the span of 2 years, Windar has grown from 2 to 12 employees. Windar realized its first turnover in 2013 for 600,000 Dkr. Furthermore the turnover in first quarter 2014 was 170,000 EUR. The EUDP project was one of the main drivers in order for Windar to achieve the current market situation. Windar is closely involved in the R&D around the WindEye lidar product. Windar's strategic commercial activities during the EUDP project have included participation in major wind energy industry exhibitions/events (see Fig. 1), setting up of a reputable distribution network (e.g. signing up FT Technologies as its product distributor), as well as gathering of detailed system specifications/requirements from lidar customers.


HUSUM Wind - Sep 2012


CanWEA - Oct 2012


WindPowerIndia - Nov 2012


EWEA - Feb 2013

Fig. 1. Different events where Windar's WindEye sensor was exhibited.

III. WP-2: Laser wind sensor prototype design

The design of the laser wind sensor prototype was based on extending the functionality of the all-semiconductor laser wind lidar system demonstrated in the paper PJ Rodrigo and C Pedersen, Optics Letters **37**, 2277 (2012). In that work, only the scalar radial wind speed component along the laser line-of-sight (LOS) can be probed by the lidar sensor. To extend the lidar functionality for measuring both wind speed and (horizontal) direction, a two-LOS laser wind sensor was envisioned. Other commercial wind lidar competitors incorporate this speed-and-direction functionality into their products (like ZephIR and Galion) by means of mechanical beam scanners (based either on rotating Risley prisms or mirror pairs) that are however expensive, bulky and prone to wear and tear. Our approach makes use of a low-cost non-mechanical beam-steering system based on simple optical devices. We have filed a patent for this lidar beam-steering approach, C Pedersen, PJ Rodrigo, and TFQ Iversen, Multiple directional lidar system (WO2013139347A1). After a series of lab tests and component considerations, we have designed an embodiment of the two-LOS beam-steering approach as shown in Fig. 2 (milestone M1).

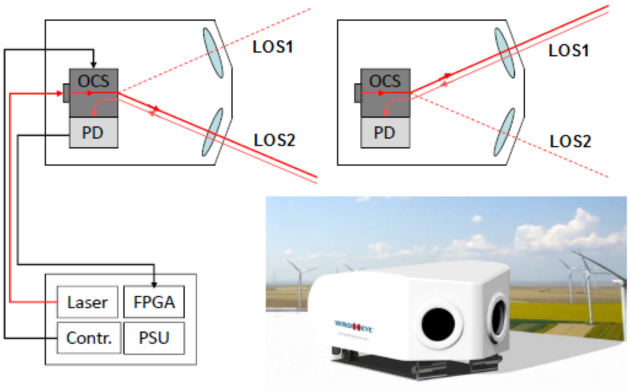

Fig. 2. The WindEye prototype design. It makes use of an optical circulator/switch (OCS) to non-mechanically steer the transmitted laser beam to either LOS1 or LOS2 and to direct the received backscatter to the photodetector (PD). The laser, controllers, power supply unit (PSU) and the FPGA-based data processor are linked to the two-eyed optical transceiver head by 10 m long fiber and electrical cables.

IV. WP3: Production of prototypes (Windar's WindEye sensors)

For this work package, Windar collaborated with external suppliers and sub-component integrators including Fideltronik in Poland (electronics), OZ Optics in Canada (optical circulator) and Brdr. Paulsen Entreprise in Denmark (mechanical parts). Windar performed the final assembly and test of the first systems. Some of the realized prototypes are shown in Fig. 3 (milestone M2).

Fig. 3. WindEye lidar prototypes each consisting of compact two-eyed optical head (transceiver) and control unit connected by a 10 m cable.

Performance characterization of these first prototypes in terms of the probing distance *R* and spatial resolution Δ*R* on both LOS1 and LOS2 was conducted in cooperation with DTU Fotonik partners. The procedure used to measure these two parameters are described in our recent work, Q Hu, PJ Rodrigo, TFQ Iversen, and C Pedersen, Optics Express **21**, 25670 (2013), and also expanded in a conference paper presented at Photonics West last February 2014, Q Hu, PJ Rodrigo, TFQ Iversen, and C Pedersen, Proc. SPIE **8992**, 89920T (2014). As shown in Fig. 4, the so-called spatial weighting functions empirically obtained for LOS1 and LOS2 of a WindEye prototype specify the respective *R* and Δ*R* of the sensor. The other WindEye prototypes were found to show similar weighting functions indicating an adequate degree of reproducibility for *R* and Δ*R* values – specified to be 80-95 m and 20-30 m, respectively.

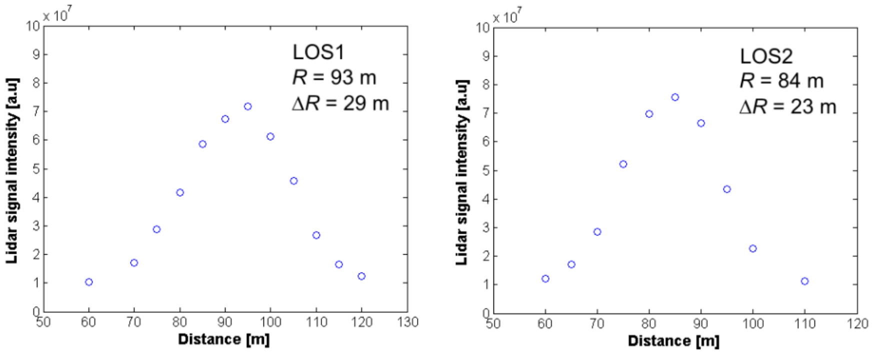

Fig. 4. Spatial weighting function for LOS1 and LOS2 of a WindEye prototype.

Aside from the weighting function, other relevant parameters describing the properties of the WindEye protoypes were determined (milestone M3). A list of these initial specifications is given in Table 1.

(Eye-safe) Laser Wavelength	1530 - 1550 nm
Semiconductor Laser Power (@ exit of 1 m fiber pigtail)	500 mW (typ.) – continuous wave
Insertion Loss (transmit beam power ÷ 500 mW)	~2 dB
Probing Distance, *R*	80 - 95 m
Spatial Resolution, Δ*R*	20 - 30 m
Separation Angle between LOS1 and LOS2	60 deg
Update Rate for LOS1 or LOS2 speed estimates	33 Hz
Update Rate for wind direction (and speed magnitude)	1 Hz
LOS speed dynamic range	2 - 30 m/s

Table 1. Basic parameter specifications for the WindEye prototypes.

V. WP4: Prototype performance field test

To evaluate the operational performance of the WindEye, we installed one prototype lidar system on a fixed mast at the test site in Roskilde such that the lidar's LOS1 and LOS2 lie on a horizontal plane ~6 m above the ground. Two 6 m tall masts were raised at locations that closely match the measured beam focusing distances *R* along LOS1 and LOS2 of the WindEye (Fig. 5). Two mast-mounted sonic anemometers (Metek USA-1, Germany) were used as reference wind sensors.

Fig. 5. Geometrical configuration of the field test at DTU Wind Energy in Roskilde to compare the performance of a WindEye prototype against reference sonic anemometers. The WindEye is facing a westerly direction.

The field test covered three months of continuous operation (except for a few short-period fall-outs like power and software interruptions) during which the prototype was measuring the wind in various weather conditions (e.g. varying air humidity and temperature, and occasional rain). Figure 6 shows some results of the performance evaluation for LOS1 (data for 12 Jan 2014 13:00-14:00). Figure 7 shows the data for LOS2. Finally, Fig. 8 shows that the horizontal wind direction measured by the WindEye is in good agreement with those measured by the two reference sonic sensors (milestone M4). A more detailed discussion of these empirical results was presented in a recent lidar conference – M Sjöholm, E Dellwik, Q Hu, J Mann, C Pedersen, and PJ Rodrigo, 17th International Symposium for the Advancement of Boundary-Layer Remote Sensing (Auckland, New Zealand, Jan 2014). A manuscript related to the detailed study of the field test data is to be submitted to a special issue of a remote sensing journal (milestone M5).

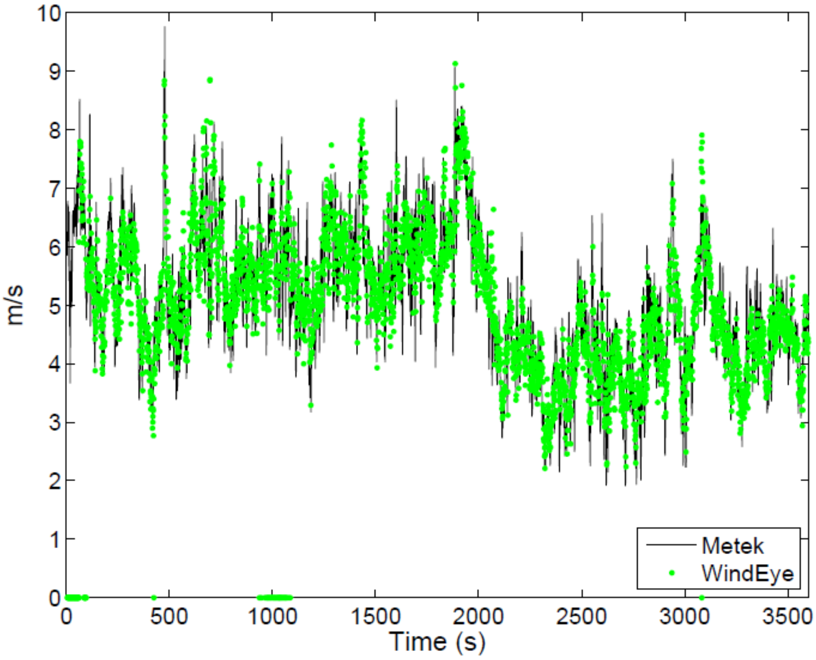

Fig. 6. Radial wind speed along the WindEye's LOS1 measured by the lidar and the sonic anemometer.

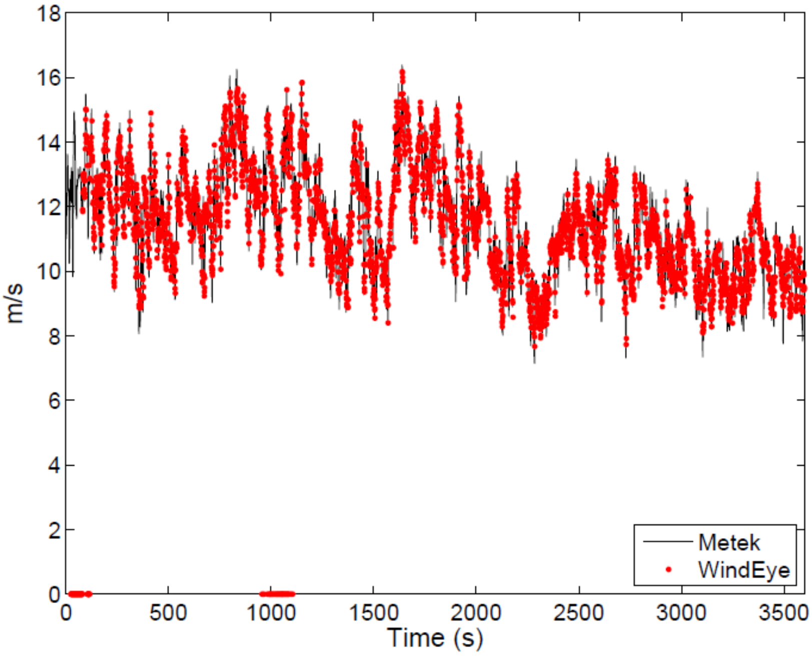

Fig. 7. Radial wind speed along the WindEye's LOS2 measured by the lidar and the sonic anemometer.

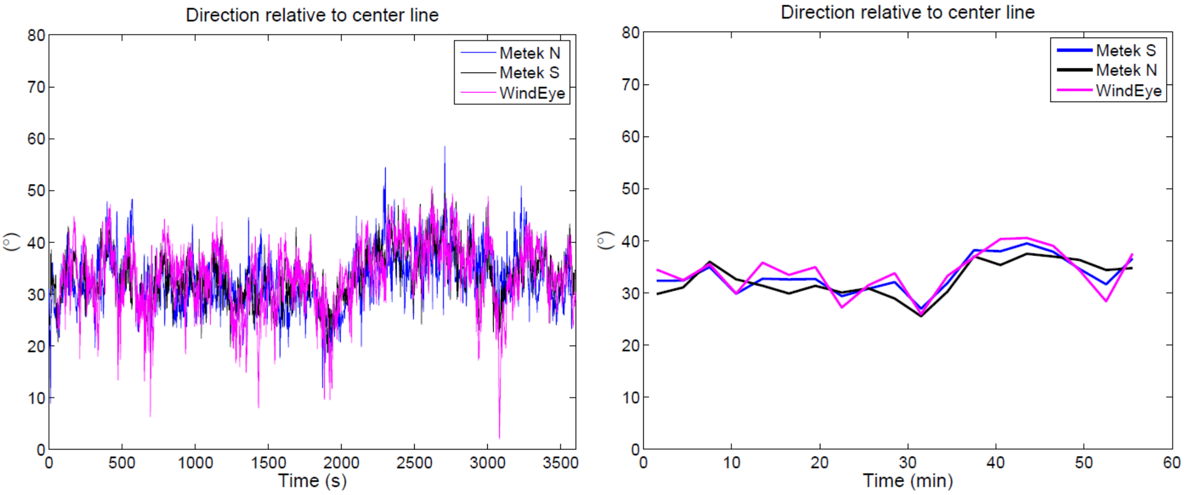

Fig. 8. Wind direction relative to the symmetry axis between the WindEye's LOS1 and LOS2 as measured by the lidar and the two sonic sensors (Metek N and Metek S). The left plot uses 1 s time bins and the right plot averages the data into 3 min time bins.

With these empirical data and other certification tests, the WindEye specification sheet partly given in Table 1 can now be further expanded with the additional parameters given in Table 2 (milestone M6). A higher r^2 value (i.e. degree of correlation between lidar and sonic speed estimates) is observed for the 3 min sampled data than for the 1 s case, due to the inherent low-pass filtering (smoothening) effect to the 1 Hz rate lidar data series due to spatial volume averaging. Another source for the observed difference between the two instruments is that the masts, where the sensors are mounted, may have moved in the wind. By choosing a low measurement height, we could advantageously measure the position of the lidar beam directly. However, the near-surface flow is typically associated with higher levels of turbulence and low spatial correlation. The low spatial correlation likely explains why the purple curve shows more variability than the blue and black curves in Fig. 8. At typical wind turbine hub heights, the flow is in general less turbulent and more correlated. In this sense, the WindEye was tested in a tough environment compared to where it will typically operate. Nonetheless, the good agreement between the sonic anemometers and the WindEye demonstrated in Figs. 6 – 8 is encouraging.

r^2 (lidar vs sonic radial speed) @ 1 s	0.8 - 0.9
r^2 (lidar vs sonic radial speed) @ 3 min	~0.99
Wind Direction Resolution @ 1 s	◁ 1 deg
□Wind Direction Lidar – Wind Direction Sonic□ @ 3 min	0 - 5 deg (see Fig. 8)
Optical Head: W x D x H, Weight, IP-rating	300 x 440 x 190 mm, 17 kg, IP65
Control Unit: W x D x H, Weight, IP-rating	255 x 430 x 110 mm, 8 kg, IP44
Power Supply	24 VDC, 20 Amp
Data Interface	RS485, Ethernet
Operating Temperature Range	-40 to +55 deg Celsius
Sinusoidal and Random Vibration Test	IEC 60068-2-6, IEC 60068-2-64, IEC 60068-2-27
EMC Test	EN-61000-4-2, EN-61000-4-3, EN-61000-4-4, EN-61000-4-5, EN-61000-4-6, EN-61000-4-8, EN-61000-4-29
Lightning Test (Zone 0B)	EN 61000-4-5, EN-61000-4-9, EN-61000-4-10
Climate Test	IEC 60068-2-14, IEC 60068-2-1, IEC 60068-2-2, IEC 60068-2-30

Table 2. Additional specifications for the WindEye prototypes.

VI. WP5: Test of WindEye on end-user wind turbines

In this work package, we have collaborated with end-users (like Mita-Teknik) to gain access to their wind turbines (e.g. a 600 kW Vestas V44 in Rødkærsbro, Jylland). This allowed us to gain a lot of experience in terms of lidar installation on the turbine nacelle as well as develop lidar beam alignment procedures. The successful installation of WindEye prototypes on the nacelle of several wind turbines is shown in Fig. 9 (milestone M9 – similar to M7). Preliminary investigations into increased power generation and load reduction due to improved yaw alignment by WindEye-aided wind turbines are under way (milestone M10 – and essentially, M8).

Fig. 9. Images showing some of the current turbine installations of WindEye sensors.

VII. Summary and outlook

The wind energy industry is gaining interest in the pre-vision of oncoming wind in front of the turbine to optimize their control (rotor yaw and blade pitch). The value proposition includes increased power production due to better alignment of the rotor to the mean wind direction as well as prolonged lifetime of the turbine due to load reductions.

Several turbine-mounted lidar wind sensors are now commercially available. However, they suffer from high price and bulkiness. In collaboration with the Technical University of Denmark, the Danish company Windar Photonics A/S, has developed a compact and low-cost lidar called WindEye based on a mass-produced all-semiconductor laser. The instrument is a coherent continuous-wave lidar with two fixed-focus telescopes for launching laser beams in two lines-of-sight with 60-degree separation angle. The alternation between the telescopes is achieved by a novel switching technique without any moving parts. In this final report, we presented empirical results from comparison campaigns with ultrasonic anemometer measurements at a distance of about 80 to 90 meters from the lidar instrument. The influence of the finite spatial sampling volume at this range on the measured wind spectra is demonstrated. The sampling volume in the latest version of the instrument has been narrowed due to an improved telescope design. Good reliability is essential for the anticipated applications for wind turbines. Thus, the lidar has been tested over extended periods in various meteorological conditions. This novel lidar instrument offers a promising low-cost alternative for pre-vision remote sensing of wind turbine inflow.