Assessing the metrological capabilities of Wind Doppler Lidars

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Since lidars are becoming industrial instruments, it is mandatory to ensure a good traceability of parameters and performances for all users. For most Doppler lidar applications, an accurate metrology is required, first of course for the radial wind component, but also for range and line of sight direction. In order to give to the user the more reliable information about its products, Leosphere is conducting a metrology plan, based on theoretical assumptions, simulation computations and experimental validations.

1. Introduction

During the last 5 years, LEOSPHERE has developed and manufactured a full range of Windcube Doppler lidars for wind sensing [1, 6]. Applications include wind energy site assessment, wind turbine verification and control, operational meteorology and airport hazard monitoring [2]. All lidars use the same fiber laser technology at 1550nm in pulsed MOPA operation [3,4,5] but vary by their laser power, telescope aperture, scanning possibilities and signal processing. So far, as more than 300 Windcube lidars have been manufactured and deployed all around the world, a full industrialization process has been setup in order to ensure the reliability of each unit and its specifications as well.

2. Position of the problem

Because the propagation and interaction medium is the atmosphere, constantly changing in time and space, it is somehow difficult for long range lidars to extract from experimental data the intrinsic characteristics of the instrument.
The current document is a first attempt to define good practices, leading possibly to future standardization documents. It refers mainly on long range scanning wind lidars, even if some common methodology exists with wind vertical profilers. Basically, the following parameters have to be defined and validated:

Velocity	**Range**	**Angle**
Measurable radial velocity range Velocity standard deviation Velocity offset	Measurable range Range resolution Range standard deviation Range offset	Angle resolution Backlash Absolute angle error

Table 1: Lidar parameters to be validated

To assess the metrological performance of the instruments, different methodologies have been developed. They refer either on experimental measurements [9], comparison with other sensors or signal processing.

3. Velocity

Several parameters can have an influence on the accuracy on wind speed measurements of coherent Doppler lidars. The wind vector is computed thanks to the combination of radial wind speeds measured on several lines of sight, like in Doppler Beam Swinging mode (DBS mode). In coherent lidars, radial velocity is directly retrieved from the Doppler shift [10]. Vr= Fd/2. The bandwidth upper limit is given by the detector chain cutoff frequency which is known by design. In heterodyne setup, the bandwidth is shared between negative and positive velocities defining the velocity range [10]. It is possible to tune the operational velocity range to the application with a digital bandwidth filter in order to decrease the false alarm probability.
The theoretical velocity error can be estimated from relations taking into account the pulse duration, the CNR and the number of averaged spectra [11] . This theoretical lower bound is often exceeded in practice. This is why this is important to measure all the parameters that could influence the accuracy on wind measurements.

Potential velocity offset could come from frequency difference between the Master Oscillator and the Power Amplifier output, due to non-linear effects in the amplification medium. This phase modulation is however quasi linear and leads to a pure frequency offset with negligible dispersion. In order to correct this bias, the laser frequency offset is measured during the validation process in the factory for each lidar and subtracted in the

signal processing settings. Other internal and external parameters of each lidar are also measured or controlled during the manufacturing process such as zero distance bin and noise level.
At the final stage of the manufacturing process, Leosphere validates the accuracies of the 10' averaged wind speeds and directions for each manufactured wind lidar.
The validation is performed by comparing each lidar with a certified short range vertical wind profiler (Windcube7v2) during one week at least. This reference lidar has been validated against a certified met mast [10, 14] during a long period, typically three to six months. These processes of validating Doppler wind lidars are currently under investigation in the IEC [14] and ISO [13] standards.
For validating a scanning lidar, the same configuration (DBS 28°/zenith) as the reference profiling lidar is used. The results show a good correlation between the two sensors, even if their spatial and time resolutions are different: 100m for the scanning lidar whereas the profiling lidar is using a 20m resolution. In the example displayed on *Figure 1*a), the biases on wind speed and wind direction are respectively 0.04 m/s and 0.36° at 200m.

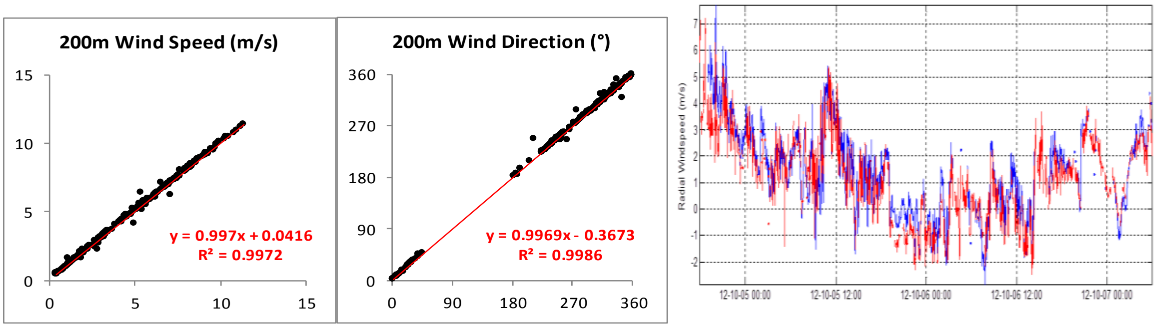

Figure 1 : a) Correlations on 10' averaged wind speed and direction between a scanning lidar and a certified profiling lidar. b) Temporal evolution of radial wind speed of scanning lidar and projected wind speed of profiling lidar during 2 days.

Another test can be performed with the scanning lidar pointing above a profiling lidar located at typically 1 km. The radial wind speed of the scanning lidar is compared to the projected wind speed of the profiling lidar. As illustrated by *Figure 1*b, the evolutions of the wind speeds measurements for the two lidars are very similar.

In addition to the systematic validations performed in the lidar factory, external tests can be realized on-demand or during the development phases of new lidars.
For validating the wind measurements at the lowest altitudes, the intercomparison can be performed with a met mast which is certified under the MEASNET standards for instance [16]. The *Figure 2 a)* represents the correlation graph on 10' averaged horizontal wind speed between a Windcube200S and a certified anemometer at 116m above the ground. The observed bias is less than 0.05 m/s.

To validate the wind speed accuracy all along the planetary boundary layer, a wind Doppler lidar can also be compared to radiosoundings, radars or UAVs in test beds like the ones that compose the GRUAN (GCOS Reference Upper Air Network). This network is considered as the reference network of ground-based observations for meteorology and climate. This is why several campaigns have been performed by Leosphere at several sites like Lindenberg (DWD, Germany) or Beltsville (NOAA, US). The Figure2 b) displays the comparison of a scanning lidar with the radar of Lindenberg observatory of the DWD German Meteorological Office in Germany [15]. The accuracy obtained for the wind speed was 0.34 m/s and 5.2° for the wind direction compared to the radar. The bias on wind direction comes mainly from the coarse alignment to the North.

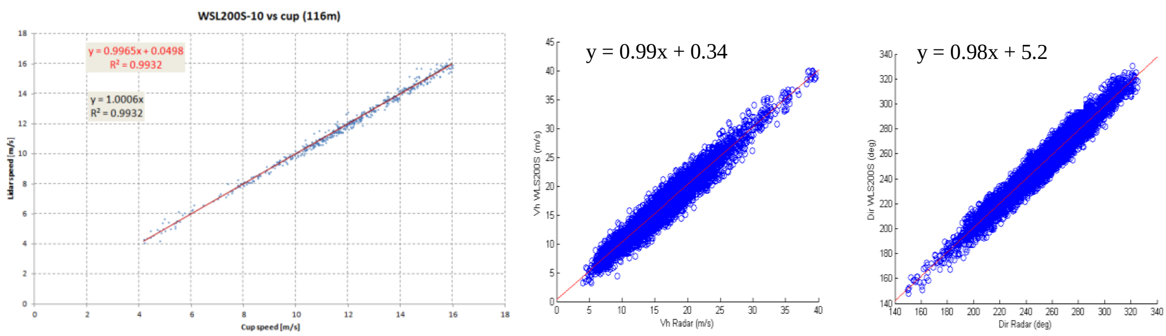

Figure 2 : a) Correlations on 10' averaged wind speed at 116m between a scanning lidar and a certified met mast. b) Correlations on 10' averaged wind speeds and directions along the PBL between a scanning lidar and a reference radar.

Usually, no reference met mast or remote sensors are available for performing the validation of Wind Doppler lidars. Leosphere encourages a revision of standards, where a lidar could be validated with a lidar which has been previously validated against a certified met mast. Today, all the manufactured lidars in Leosphere are compared to a reference lidar validated against a reference met mast at DTU Wind Energy (DK).

4. Range

If the accuracies on the velocity measurements are crucial for the quality of lidar measurements, range or distance accuracies are also required.
The minimum range is the center of the first range gate where the velocity is not biased by the transmitted pulse echo in the telescope. The minimum range is about twice the range resolution. During validation process, velocity bias is controlled in the first range gate.
The maximum range is indeed the most difficult parameter to estimate, since it depends on many parameters, including unknown atmospheric parameters. The range of lidar measurements varies with atmospheric conditions such as meteorological visibility, type of aerosols, rains, humidity rate, turbulence, and refractive index. Knowing these parameters for a specific site is almost impossible since for some of them like the type of aerosols, reference sensors are poorly available. For a 4 months campaign in France, the horizontal range obtained with a Windcube200S follows the distribution showed in *Figure 3 a)*. During this experiment, 5km range has been reached by the lidar 80% of the time.

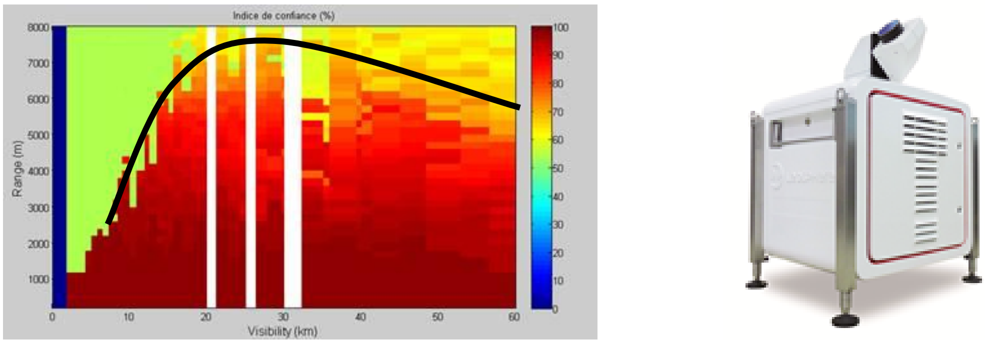

Figure 3: a) Probability of maximum range vs visibility. *b) Lidar Windcube200S from Leosphere*

The variations of the range can often be explained by the variations of atmospheric parameters. The atmospheric parameter which has the major influences on lidar range was visibility as expected. As displayed in the *Figure 3 a)*, an overall bell-curve trend can be observed between measurements range and visibility. For low visibility, the range is low because of the strong extinction. The range is maximum for hazy to clear atmosphere. If the visibility if however very high, the range is decreasing because of the lower aerosol concentration. These observations are confirmed by lidar simulations [16] that also highlight the influence of Lidar Ratio associated to the type of aerosols. As all the parameters can vary at the same time, determining the effective influence of each atmospheric parameter is difficult with real data.

Concerning the range resolution, the velocity at a given range is in fact the weighted contribution of velocities along a probed volume. The width of this weighting function is the physical range resolution. It is assessed by using semi-transparent hard targets measurements. CNR (Carrier to Noise ratio) at null velocity is then computed for different range gate centers, around the target. Typical results are displayed in *Figure 4*.
The spatial resolution of a range gate at full width of half maximum (FWHM) is 26.9 m for a pulse duration of 180 ns. A lidar simulation tool [16] is also used to check the theoretical resolution as the convolution of the pulse and the range gate. The simulation gives a range resolution of 29 meters.

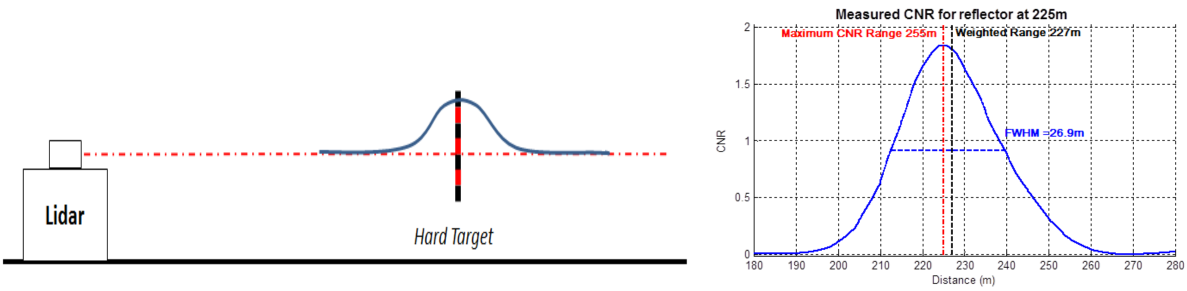

Figure 4 : a) Setup of the range gate resolution tests. b) Results obtained

5. Angles

The assessment of the error in scanning head position, both zenithal and azimuthal is realized thanks to a calibrated theodolite sensor. This sensor is fixed to the scanner head. The evaluation of the accuracy of the scanner head position in azimuth/elevation is then performed among a large number of successive PPI/RHI scenarios (Plan Position Indicator at constant elevation / Range Height Indicator at constant azimuth). The mean deviation in scanner position is 0.001° and the standard deviation is 0.009° that leads to an acceptable 2.3m error at 10km. The backlash is less than 0.05°. These accuracies measured on scanning lidars ensure the specifications of the lidars.

6. Conclusion

Coherent Doppler lidars are now becoming standard wind sensors for operational applications in wind energy and airport meteorology. This requires the ability for the industry to ensure the performances of each manufactured lidar. To do so, Leosphere is developing industrial lidars with dedicated internal control and validation processes. In addition, external validations are performed in reference test beds to demonstrate the performances of the instruments during the development. In parallel, several expert groups are working on the standardization of coherent Doppler lidars for sharing common definitions and key principles of measurements in order to help the users.

7. References

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