Classification of lidar profilers
or: how to introduce lidars to power performance testing

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Summary

Commercially available lidars have reached a level of accuracy where they can be considered as serious alternative to standard cup anemometers – especially with significant advantages in large heights or in areas where it is difficult and costly to set up a measuring mast. A further benefit is that lidars can measure wind speeds and wind directions simultaneously at different height levels, why they are particularly suited for the measurement of vertical wind shear.

A standardized application to power performance testing (as well as more generally resource assessment), however, requires a traceable classification scheme that allows for a complete evaluation of the uncertainty of the measurements performed by the lidar. Furthermore, a corresponding verification test may be the basis for a calibration of the lidar with respect to one or more reference sensors.

The procedure of lidar evaluation, we propose, is based on the verification of a ground-based lidar profiler against a tall meteorological mast that is equipped with reference sensors at different height levels. Following the recommendations for the testing and evaluation of cup anemometers in the IEC 61400-12-1 standard, the verification test is analysed in terms of both a calibration and a classification of the tested instrument. In this way, traceability is transferred from the reference sensors to the tested lidar and a respective lidar uncertainty is deduced accordingly. Our investigations are focussed on how to interpret the observed deviations between the lidar and the reference sensors in terms of measurement uncertainties. The formulation of a full classification scheme for lidar profilers is however still in progress and not presented in this paper.

The work summarized in this paper has been carried out as part of the EU FP6 UpWind project (work package 6) and is directly connected to IEC MT12-1 currently revising the IEC 61400-12-1 standard for power performance testing – for this purpose, in 2009 the Lidar Acceptance Project was initiated to coordinate the work in a satellite group complementing the IEC maintenance team.

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1 Concept of lidar verification

The term verification test is used for the comparison of lidar measurements to the readings of traceable reference sensors, i.e. cup anemometers and wind vanes, at different heights and under a set of pre-defined external conditions. Due to the different measurement principles (a volume measurement is compared to a nearly point measurement, cf. figure 1), the correlation between the lidar and the reference measurements is a priori limited. Accordingly, a certain basic uncertainty is introduced that is attached to the lidar measurements when requiring a traceability from the reference sensors to the lidar in terms of this verification concept.

Typically, the obtained data sets (measured wind speeds and directions recorded as 10-min mean values) are filtered with respect to a set of well-defined criteria, in order to achieve a certain level of repeatability of the test, and then analysed in

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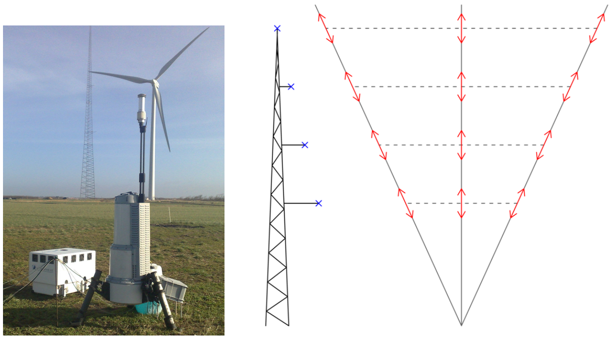

Figure 1: Setup of verification test – meteorological mast equipped with reference sensor and ground-based lidar. Blue crosses show the locations of the reference sensors, red arrows indicate the measuring volumes of the lidar.

terms of a linear regression (cf. [2]). Figure 2 shows the results for three different linear regression approaches, defined by the model equations $y = C + kx$, $y = mx$ and $y = D + k_u x + k_g g$, respectively, where y is the wind speed measured by the lidar, x the corresponding reference wind speed and g the local wind speed gradient (as defined in [3]). For the evaluation of wind direction measurements, only the first model, i.e. a one-parametric linear regression with non-zero offset, is applied.

The evaluation of the verification data in terms of a regression analysis may be the basis for a calibration of the lidar (if applied; more details in the next section). Calibration would then mean to correct for a systematic bias that is observed under the conditions of the verification test. Since the external conditions for the verification test are indeed limited (by the filtering criteria) but not absolutely fixed as it is required for an exact (stable) calibration, the verification test should be interpreted at the same time as a lidar classification (with respect to the observed and included conditions). A corresponding classification uncertainty for the lidar (cf. the uncertainty due to operational characteristics referred to in IEC 61400-12-1 [1]) is derived from the statistics of the lidar error, i.e. the deviation between the 10-min mean values of the lidar and the reference measurements.

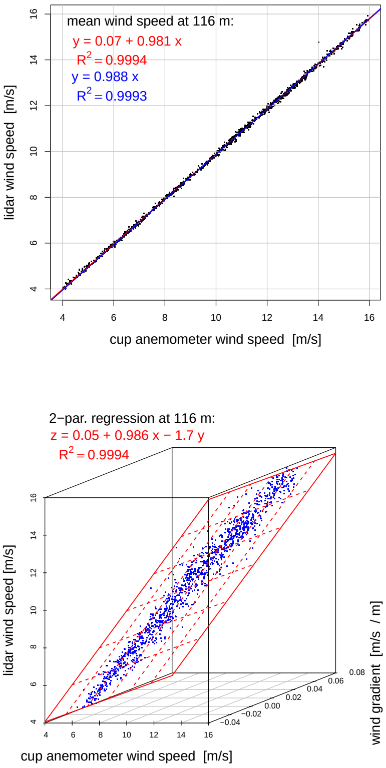

Figure 2: Results for different regression models – (top) one-parametric regression with and without offset, (bottom) two-parametric regression. The plots are to be understood as examples. A complete test study is not within the scope of this paper.

2 Estimation of uncertainties

The uncertainty budget for the final lidar measurements consists of the following components:

- the reference uncertainty, i.e. the combined uncertainty of the respective reference measurement ($u_{\mathrm{ref.}}$),
- the lidar calibration uncertainty, defined by the uncertainty of the calibration function (if a calibration is applied; $u_{\mathrm{lid.cal.}}$) and
- the lidar classification uncertainty (with respect to the range of external conditions covered in the verification test; $u_{\mathrm{lid.class.}}$).

In addition to these three basic components (that are defined in more detail below) there might be an extra uncertainty due to the mounting or setup of the lidar. Furthermore, an additional uncertainty due to specific (external) conditions during the application that are not covered by the verification framework is so far not considered – but should be included in a more extensive classification approach.

In the following, the individual basic uncertainty components are discussed only for the wind speed measurements in more detail – uncertainties for the wind direction measurements are to be evaluated in a similar way.

According to IEC 61400-12-1 [1], the combined uncertainty of a cup anemometer measurement is the sqare root of the sum of squares of the following uncertainty components:

uncertainty of anemometer calibration ($u_{\mathrm{V1},i}$),

uncertainty due to operational characteristics ($u_{\mathrm{V2},i}$),

uncertainty of flow distortion due to mounting effects ($u_{\mathrm{V3},i}$),

uncertainty of flow distortion due to terrain ($u_{\mathrm{V4},i}$)

and uncertainty in the data acquisition system ($u_{\mathrm{dV},i}$).

Figure 3 illustrates how the single components add up to the total uncertainty, i.e. $u_{\mathrm{V},i} = (u^2_{\mathrm{V1},i} + u^2_{\mathrm{V2},i} + u^2_{\mathrm{V3},i} + u^2_{\mathrm{V4},i} + u^2_{\mathrm{dV},i})^{1/2}$, with some typical numbers from the instruments used in our verification tests. The (combined) uncertainty of the cup anemometer measurements is directly passed on to the lidar measurements as reference uncertainty, i.e. $u_{\mathrm{ref.}} \equiv u_{\mathrm{V}}$.

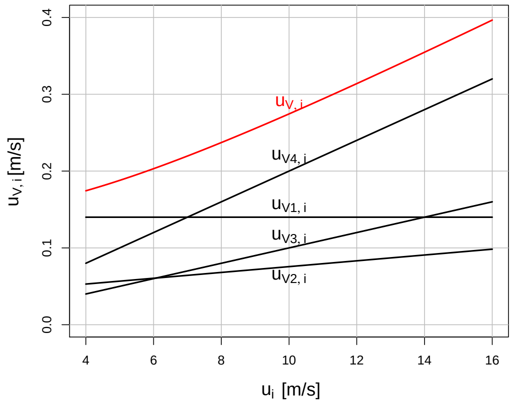

Figure 3: Reference uncertainty components of cup anemometer measurements according to IEC 61400-12-1 – $u_{\mathrm{V1},i}$ $(0.14m/s)$, $u_{\mathrm{V2},i}$ $((0.05\ \mathrm{m/s} + 0.005 \cdot u_i) \cdot k/\sqrt{3};\ k = 1.31)$, $u_{\mathrm{V3},i}$ (1%), $u_{\mathrm{V4},i}$ (2%), $u_{\mathrm{dV},i}$ (–).

The lidar calibration uncertainty ($u_{\mathrm{lid.cal.}}$), as second component in the lidar uncertainty budget, is defined by the uncertainty of the applied calibration function, i.e. basically the standard uncertainties of the estimated regression parameters. In case no calibration is applied, the calibration uncertainty is omitted but generally a larger classification uncertainty is expected.

The (test-specific) lidar classification uncertainty ($u_{\mathrm{lid.class.}}$) is directly deduced from the statistics of the observed values for the lidar error (see definition above). It is test-specific since it is (strictly speaking) only valid with respect to the range of external conditions covered in the verification test. We propose to estimate this uncertainty component not on the basis of the observed extreme deviations and the assumption of a rectangular distribution of the deviations, as done for the cup anemometer classification (cf. [1]), but to consider the actual observed distribution and derive the square root of its non-centred second moment – i.e. $\tilde{\sigma} = (\sum_i \epsilon_i^2/(N-1))^{1/2}$ with ϵ_i as the lidar error. For distributions of ϵ_i non-symmetric around zero, i.e. when the lidar measurements are significantly biased with respect to the reference measurements, the square root of the non-centred second moment is always larger than the simple standard deviation. Note, however, that the level of confidence is generally over-estimated by this simple measure. (The range $\pm\tilde{\sigma}$ covers less than 68.27% of the observed values for ϵ_i.)

Figure 4 illustrates how the lidar classification uncertainty, defined as proposed above, is reduced by applying a calibration to the lidar measurements. The reduction is up to 50% for single wind speed bins. The calibration uncertainty, that has to be added, is on the other hand insignificantly small. The combined lidar uncertainty is the square root of the sum of the squared individual uncertainty components (listed above), and it is evaluated per 0.5 m/s-bin (cf. [1]).

3 Discussion

The presented lidar verification scheme prepares the basis for

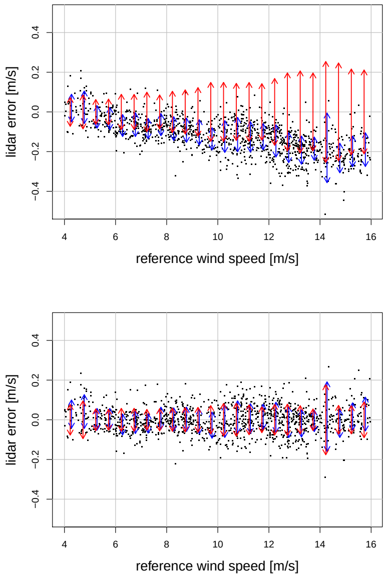

Figure 4: Standard deviation (blue arrows) and square root of second moment ($\tilde{\sigma}$ as estimate for symmetric uncertainty; red arrows) of lidar error for individual wind speed bins – (top) before and (bottom) after calibration of lidar wind speed values applying the obtained regression function (here: results for two-parametric model).

- traceable lidar measurements (with respect to the reference sensors),
- repeatable lidar measurements (with respect to a well defined uncertainty budget),
- a consistent evaluation of lidar uncertainties (in line with IEC 61400-12-1 [1] and GUM [4]).

The results of the verification test are evaluated as calibration and as classification at the same time – with the drawbacks that the calibration functions depend on the specific external conditions and only a certain range of possible conditions is covered by the classification. An expanded classification uncertainty should be estimated by considering a wider range of conditions and on the basis of more extensive verification tests for some selected lidar units.

The lidar calibration is based on a reference that is itself associated with a significant uncertainty. A necessary assumption is that the reference is non-biased and that the uncertainties are symmetrically distributed around the mean estimate (cf. [4]). The use of reference sensors with a lower uncertainty directly reduces the final uncertainty of the lidar measurements.

Lidar calibration functions depend not only on the actual site conditions (e.g. (global) vertical wind shear) but also on the measurement height (i.e. the local shear). Extrapolations between the verification test and the application are to be considered.

References

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