HOW TO GAIN ACCEPTANCE FOR LIDAR MEASUREMENTS

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Summary

Technical requirements for the application of ground based lidars or sodars for wind measurements in the frame of wind turbine power curve testing and wind resource assessments have been worked out in the frame of the revision of the standard IEC 61400-12-1 mainly by the Lidar Acceptance Group. These requirements are aiming to ensure the traceability, repeatability and a full survey of uncertainties of lidar/sodar measurements in order to provide the basis for acceptance of such measurements. Core requests are an Accuracy Test/Calibration of each individual lidar/sodar unit as well as a type specific Sensitivity Test/Classification of lidars and sodars, which are (for the time being) both based on a comparison of lidar/sodar measurements to cup anemometer measurements on high met masts. The best remote sensing devices seem to be just acceptable for flat terrain applications.

1 Introduction

Wind speed measurements by lidar have gained a lot of interest in the wind energy industry over the last years. Furthermore, wind measurements by means of met masts become more and more impracticable, especially as there is an increased need to measure over the whole rotor height range of wind turbines. Consequently, the maintenance team of the standard IEC 61400-12-1 [1] for wind turbine power curve testing is considering the introduction of lidar/sodar measurements as a supplementary or alternative measurement technique to cup anemometer measurements for the next revision of the standard. This process is supported by the Lidar Acceptance Project, which is aiming to deliver the technical basis for the acceptance of lidar measurements for wind turbine power curve testing and wind resource assessments. In this frame, requirements for the validation and application of lidars have been worked out.

2 The Lidar Acceptance Project

The main technical input for the revision of the standard IEC 61400-12-1, Edition 1 had to be delivered until autumn 2010. In the beginning of the year 2009, the technical basis for the integration of wind measurements by remote sensing devices like lidars and sodars in this revision was relatively poor. On the other hand, promising experience with lidar wind measurements existed already [2]. This was the reason for some key experts with significant experience in the application of lidar for wind engineering purposes to set-up the Lidar Acceptance Project with the aim to develop the technical basis for making lidar wind measurements acceptable for the maintenance team of the standard IEC 61400-12-1 in a very short time frame from May 2009 to autumn 2010. Participants of the project are the wind turbine manufacturers Vestas, Siemens and Enercon as well as the testing laboratories Riso-DTU, GL Garrad Hassan and Deutsche WindGuard (project leader). The project participants work in close collaboration with the maintenance team of the standard IEC 61400-12-1. Due to the limited time frame, only ground based remote wind sensing devices are considered within the project. The derived procedures and recommendations are not limited to lidars and can also be applied for sodar measurements.

3 Key Requirements

The key requirements identified in order to gain acceptance for wind measurements by lidars/sodars are:

- The measurements must be traceable to national standards.
- The measurements must be repeatable under any environmental conditions.
- A complete analysis of the measurement uncertainties is required.

Technical solutions to accomplish these requirements have been developed and tested and are described in the following chapters.

4 Accuracy Test / Calibration

Unlike cup anemometers, lidars and sodars cannot be tested in wind tunnels due to the large size of the wind scanning volume. In principle, it would be possible to trace back every measurement device, the complete data processing and the complete system assembling involved in a lidar or sodar back to national standards. However, it was concluded that this way would be too complicated for the time being and under consideration of the available time frame. As a consequence, the only way to gain traceability to national standards is to compare each individual lidar and sodar to calibrated reference sensors in open field tests. As the only available traceably calibrated reference sensors for open field tests are cup anemometers, this means that each individual lidar or sodar should be tested against a properly equipped high met mast. Test masts especially equipped for tracing back lidars and sodars exist so far in Germany [2] and at Riso/DTU [3]. The comparison of the lidar/sodar against a reference cup anemometer must be performed in each measurement height of the lidar/sodar and shall capture the wind speed range 4 m/s to 16 m/s like cup anemometer calibrations in wind tunnels according to IEC 61400-12-1 and MEASNET [4]. There are different ways to evaluate such an Accuracy Test/Verification Measurement [5], [6]: If the deviation of the wind speed measured by the lidar/sodar to the reference cup anemometer is in each wind speed bin within the standard uncertainty of the cup anemometer measurement (plus the statistical uncertainty of the comparison), the correction of the lidar/sodar according to the cup anemometer measurements does not make much sense. It is then more appropriate to consider the wind speed measurement of the lidar/sodar as valid within the following uncertainties:

- uncertainty of cup anemometer measurement
- systematic (binwise) deviation of cup anemometer measurement and lidar/sodar measurement
- statistical uncertainty of the comparison

An example of such a comparison between a lidar and a cup anemometer is lustrated in Figure 1.
If the deviation of the wind speed measured by the lidar/sodar to the reference cup anemometer exceeds the standard uncertainty of the cup anemometer measurement (plus the statistical uncertainty of the comparison), the relation of the lidar/sodar wind speed measurement and the reference cup anemometer measurement should be applied for a calibration of the lidar/sodar. This calibration is then linked to the following uncertainties:

- uncertainty of cup anemometer measurement
- binwise residuals of calibrated lidar/sodar measurement and cup anemometer
- statistical uncertainty of the comparison

In any case, the Accuracy Test/Calibration cannot be more accurate than the cup anemometer measurement. This limitation will remain until other, more accurate reference sensors are available.

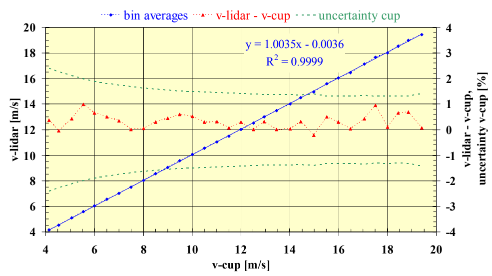

Figure 1: binwise comparison of a lidar of type Windcube V1 to a cup anemometer at a measurement height of 135 m.

5 Sensitivity Test / Classification

The accuracy of lidar/sodar wind measurements, like cup anemometer measurements, is dependent on environmental conditions, like e.g. the wind shear, turbulence intensity, wind veer and other variables. As the environmental conditions during the Accuracy Test/Calibration of the lidar/sodar deviate from the environmental conditions present during the application of the lidar/sodar for a wind turbine power curve test or wind resource measurement, the uncertainty of the lidar/sodar wind measurements due to its sensitivity to environmental variables needs to be assessed and taken into account.
An outline for a type specific Sensitivity Test/Classification Scheme for lidars/sodars has been worked out [7], which is very similar to the existing classification of cup anemometers according to IEC 61400-12-1 [1]. The measurement set-up of the Sensitivity Test is basically the same than in case of the Accuracy Test/Calibration. The sensitivity of the accuracy of the lidar/sodar on a set of environmental variables is analysed for each measurement height covered by a reference met mast. The percentage deviation of the lidar/sodar and the cup anemometer per 10-minute period is considered as function of one environmental variable at a time. The sensitivity of the lidar/sodar measurement on that variable is basically expressed by the slope of a linear regression fitted through the data. Examples for such sensitivity tests on the wind shear in case of a lidar of type Windcube Version 1 and a certain type of sodar are shown in Figure 2 and Figure 3, respectively. In general, the wind shear turned out to have a quite large influence on different types of lidars and sodars, and the influences are also dependent on the measurement height. In case of two commercially available types of lidars influences of the wind shear in the order of +/- 1 % on the wind speed measurement have been observed. In case of the sodar analysed in Figure 3, the influence is about 5 %, what is unacceptably high and what also was not expected by the referring manufacturer of the system.
Maximum expected ranges of environmental variables are considered for a classification of lidars/sodars as is illustrated in Table 1. The regression slope of the sensitivity test times the range of the environmental variable results in the maximum influence of the considered environmental variable on the measurement of the lidar/sodar. Only significant environmental variables should be considered for the classification, while a first approach for the elimination of insignificant variables is proposed in reference [7]. Furthermore, a first proposal for cumulating the influences of the different environmental variables to a possible total measurement error of the lidar/sodar due to the influence of these variables is given in reference [7].
First classification results for a lidar of type Windcube Version 1 and a certain type of sodar are shown in Table 2 (same sodar than for Figure 3). The class numbers must be understood as maximum percentage measurement errors in terms of the wind speed. These values should be divided by $\sqrt{3}$ for representing the percentage standard uncertainty due to influences of environmental conditions. The high class numbers are partly due to the considered large ranges of environmental conditions according to Table 1. The same problem exists also with the clas-

sification of cup anemometers for complex terrain conditions according to IEC 61400-12-1 [1]. Much lower maximum errors result if only the maximum deviations of the environmental variables at the application of the lidar/sodar to the mean values present at the Accuracy Test/Calibration are considered (S-classification) [7].

It is pointed out that the proof of the robustness of the classification scheme is still outstanding. Mayor concerns are:

- The cumulating of the influences of environmental variables is a challenge because the different variables are partly dependent from each other. Ideas for improvements in this respect exist, but have not yet been tested. The elimination of insignificant variables is also linked to this issue.
- the assumption of linearity of the influences of the environmental variable on the accuracy
- the proper coverage of environmental variables by field tests

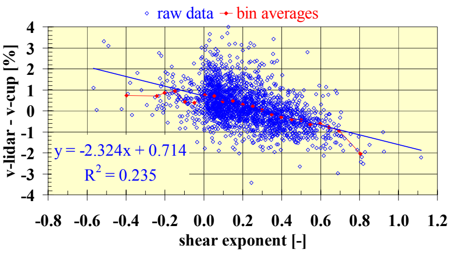

Figure 2: sensitivity analysis of accuracy of a lidar of type Windcube Version 1 on the wind shear exponent in terms of the absolute wind speed at a height of 135 m above ground

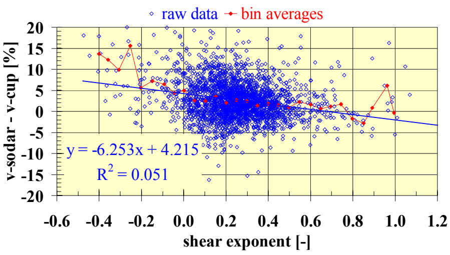

Figure 3: sensitivity analysis of accuracy of a certain sodar on the wind shear exponent in terms of the absolute wind speed at a height of 135 m above ground

		flat terrain			complex terrain			
independent variable		**max**	**min**	**range**	**max**	**min**	**range**	**source**
shear exponent alpha	[-]	0.80	-0.40	1.20	0.80	-0.40	1.20	experience
turbulence intensity I	[-]	0.24	0.03	0.17	0.36	0.03	0.33	IEC 61400-12-1
rain (yes=1, no=0)	[-]	1	0	1	1	0	1	by definition of sensor
availability lidar	[%]	100	80	20	100	80	20	by definition of filter
wind direction	[°]	360	0	180	360	0	180	deviation of 2 directions is maximum 180°
air temperature T	[°C]	40	0	40	40	-10	50	IEC 61400-12-1
air density	[kg/m³]	1.35	0.90	0.45	1.35	0.90	0.45	IEC 61400-12-1
T difference 133m-10m	[K]	6	-2	8	6	-2	8	experience
flow inclination angle	[°]	3	-3	6	15	-15	30	IEC 61400-12-1
wind veer dir133-dir35	[°]	20	-20	40	20	-20	40	experience

Table 1: ranges of environmental variables considered for a type specifc classifiaction of lidars/sodars in flat and complex terrain

instrument	height	flat terrain	complex terrain
[-]	[m]	[-]	[-]
Windcube V1	135	2.7	3.6
	104	4.9	8.1
	72	3.9	11.3
Sodar	135	8.3	10.6
	72	5.9	13.8

Table 2: first classification results of a lidar of type Windcube Version 1 and of a certain sodar system

6 Analysis of Uncertainty

The remote wind sensing devices commercially available today measure the three wind speed components in spatially separated volumes. This technique has the advantage that only one light or sound source is needed at the ground (at one position), which transmits the light or sound beam in different upward directions relative to the source. The disadvantage is that these systems assume equal wind conditions within the different probe volumes for the evaluation of the wind speed. This assumption can lead to significant measurement errors in complex terrain [8]. Thus, these measurement errors should be assessed for every application of a lidar/sodar system. If the expected error is too high, the system should not be applied. In moderately complex terrain, the choice of the measurement position can help to reduce this uncertainty component.

Mann, Bingöl and Foussekis have shown that the error associated to the measurement of the wind speed introduced by the assumption of homogenous air flow within the different probe volumes is for many instruments proportional to the variation of the vertical wind speed component between the different probe volumes and to the measurement height, so far a linear variation of the wind field between the probe volumes can be assumed [9]:

$$u_{lidar} = u + h\frac{\partial w}{\partial x}$$

As is shown in reference [10], this formula can be transformed to:

$$\frac{u_{lidar} - u}{u} = \frac{\tan\alpha_2 - \tan\alpha_1}{2\tan\phi} \quad (1)$$

where the left side represents the relative measurement error of the remote sensing device, α_1 and α_2 are the vertical flow inclination angles at opposite probe volumes, and ϕ is the cone angle of the remote sensing device (Figure 4).

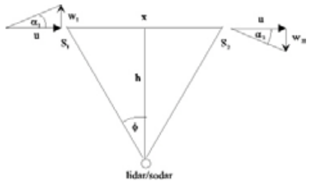

Figure 4: illustration of nomination of angles given in formula (1)

It is proposed to apply a method defined in the standard IEC 61400-1 [11] to estimate the maximum flow inclination angle in the different probe volumes. Then formula (1) can be applied to estimate the maximum lidar/sodar error due the assumption of homogenous airflow within the different probe volumes [10]. As is shown in Table 3, this measurement error gets high as soon as the variation of the vertical flow angle between the probe volumes gets significant. However, test cases have shown that this error is small for flat terrain applications [10].

α_1	α_2	relative lidar error
[°]	[°]	[%]
0	1	1.5
-1	1	3.0
-1	1	3.0
0	5	7.6
5	10	7.7
0	10	15.3
10	20	16.3
0	15	23.2
-7.5	7.5	22.8

Table 3: lidar/sodar error estimation due to the assumption of homogenous airflow within the different probe volumes (for a cone angle of 30°)

The following further uncertainty components of a lidar/sodar measurement should be considered, which in principle exist also in case of cup anemometer measurements:

- uncertainty remaining from the Accuracy test/Calibration
- uncertainty resulting from the Sensitivity Test/Classification
- uncertainty due to non-perfect mounting/alignment of the lidar/sodar
- in case of wind turbine power curve tests: uncertainty due to flow variation between the position of the lidar/sodar and the wind turbine

A first full survey of uncertainties of measurements with a lidar of type Windcube Version 1 at a site in flat terrain according to the above scheme have led to a total standard uncertainty of the measurement of the horizontal wind speed component of 2-3 %. For comparison: Best practice cup anemometry has a total standard uncertainty of about 1.5 %.

7 Definition of Wind Speed

Two different applications of lidars/sodars are discussed within the revision of the standard IEC 61400-12-1:

- measurement of the horizontal wind speed component at different height levels covering the rotor height range, or
- applying the remote sensing device only for a measurement of the wind shear. This shear measurement needs then to be combined with a measurement of the horizontal wind speed component with a cup anemometer at hub height.

Depending on the application, the Accuracy Test / Calibration as well as the Sensitivity Test / Classification of the remote wind sensing device should be performed in terms of the measurement of the horizontal wind speed component or in terms of the wind shear measurement.

8 Other Aspects

Other issues to be dealt with when applying remote wind sensing devices are:

- control of the lidar/sodar performance during the power curve measurement,
- positioning of the lidar/sodar during power curve test: The complete probe volume may have to be inside the distance range of 2 to 4 rotor diameters to the wind turbine.
- measurement of air temperature and air pressure close to hub height without mast
- evaluation of turbulence intensity
- requirements on data coverage within 10-minute intervals
- requirement of identical system parameterization during Accuracy Test/Calibration, Sensitivity Test/Classification and power curve test/wind resource measurement
- requirements on reporting

9 Current Status

The current status of lidar/sodar applications for wind turbine power curve testing and wind resource measurements can be summarised as follows:

- Lidars and sodars of almost all major brands have been tested or are currently under test by Deutsche WindGuard or by Risoe/DTU. The results are partly confidential.
- The best lidar systems seem to be just acceptable for flat terrain applications in terms of the measurement uncertainty.
- The proposed lidar/sodar classification scheme is under test by different members of the maintenance team of IEC 61400-12-1
- A round robin test of the same lidar is scheduled at the test sites of Deutsche WindGuard and Risoe/DTU
- An annex about requirements on lidar/sodar measurements has been drafted for the revision of IEC 61400-12-1.

10 Acknowledgement

Thanks belong to Enercon for making available the 135 m met mast at the German Test Station for Remote Wind Sensing Devices, which is a fundamental basis for the reported work.

11 References

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