Pitch and Roll Angle Calibration for Scanning LiDARs to Reduce Uncertainties in Measurement Height

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Summary

The application of scanning LiDARs for the measurement of wind speed is a relatively new technology in the wind energy sector and also has potential relevance for various topics (e.g. measuring wind speed for power performance tests for offshore wind turbines). Scanning LiDARs offer a customizable scanning geometry and are, therefore, able to measure wind speed and wind direction at a position that is not centered on its own position. For such situations, the knowledge of the elevation angle is crucial, as it directly influences the measurement height. For instance, for power performance tests of offshore wind turbines of typical size, accuracy higher than 0.1° is necessary. Independent from the displayed elevation angle of the device, the real inclination of the device must be known, since there might be correction factors in terms of slope and offset. Deutsche WindGuard developed a new method of calibrating pitch and roll angle for scanning LiDARs including an approach to avoid the challenge of identifying the invisible laser beam by applying an adjustable visible laser beam. The results of devices tested thus far lead to the assumption that calibration of the built-in inclinometers is recommended in order to achieve a high accuracy in elevation angle and consequently in measurement height.

Introduction:

Scanning LiDARs (Light Detection and Ranging) offer a customisable scanning geometry. The instrument can therefore be customised to measure the wind speed and wind direction at a position that is not centred on its own position.

One application is the measurement of wind speed in order to determine the power curve of an offshore turbine. The instrument is located on the transition piece of the turbine and measures several hundred meters in front of the turbine. In this configuration the knowledge of the elevation angle of the instrument is crucial, as this angle directly influences the measurement height. E.g. at a horizontal distance of 360 m and a hub height of 80 m, the IEC criterion [1] of measuring within 2.5 % of the hub height relates to an allowed scan elevation angle in the range of 12.23° to 12.83°. This shows that the vertical alignment of the instrument has to be known with accuracy better than 0.1°.

The scanning units under test display pitch and roll angle operation: In order to calculate an as precise measurement height as possible, these sensors have to be calibrated prior to a measurement. Thus far, four devices of type Galion G4000 have been calibrated in the facilities of Deutsche WindGuard.

Measurement Setup

To assess the accuracy of the pitch and roll inclinometers of the LiDAR, the real, measured elevation angle α of the laser beam in a given configuration of the instrument is compared to the output of the inclinometer. Figure 1 and Figure 2 show schematic overviews of the measurement configuration. Figure 3 shows a photograph of the setup.

The main measurement method is a direct measurement of the angle α with a theodolite that was double-checked by a direct measurement of the angle α being the relation of the vertical displacement of the laser beam and the horizontal distance from the exit lens. A clear definition of the reference height h_0 to define an angle of α=0°. This reference height is the exit point of the laser beam on the LiDAR. It is assumed that this exit point is the centre of the lens. To transfer this height across the measurement site, a rotating laser was used. Common to this approach is the challenge of finding the invisible laser beam. The wavelength of the laser is approximately 1550 nm, i.e. the laser emits in the infrared. Therefore direct detection of the outgoing laser was not feasible. The location of the laser beam was identified by iteratively blocking and unblocking the laser beam with the wooden construction shown in Figure 3. Blockage of the laser beam occurs when the LiDAR's carrier-to-noise ratio (CNR) decreases significantly for the range gate in approximately the distance of the screen and range gates behind. The CNR is monitored in real-time with a laptop connected to the instrument. A similar technique was used by DTU in their calibration of roll and pitch angle of a nacelle mounted LiDAR [2]. Since this procedure is quite time consuming, it is only performed for the first angle of a calibration. For the remaining angles, a high-class laser pointer with visible green light is used. This laser is mounted on the scanning head of the LiDAR and is positioned at a fixed but smallest possible offset from the infrared laser. A theodolite has been placed close to the LiDAR. The positions of the laser beams were targeted with the crosshair of the theodolites telescope. The angle between the horizontal and the target point is then directly displayed by the instrument.

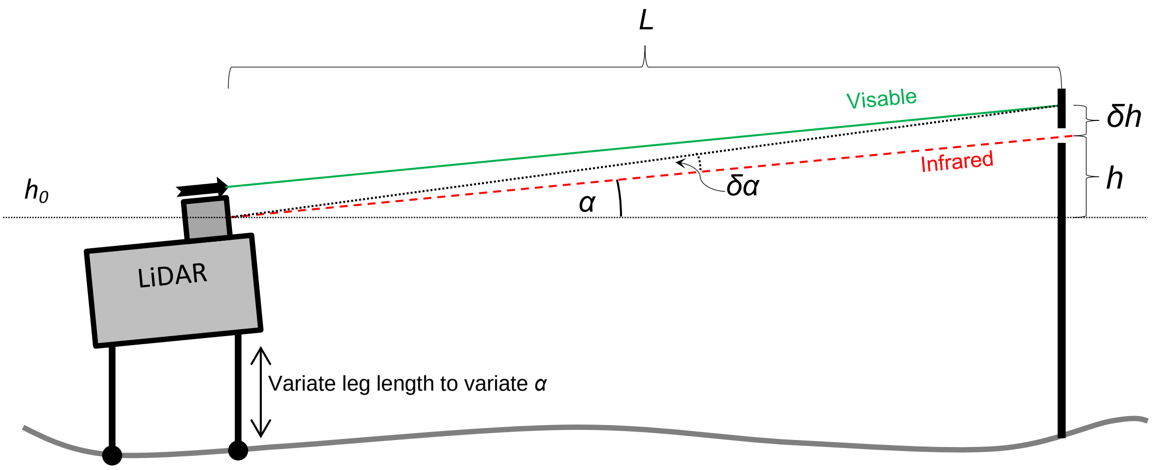

Figure 1: Schematic side view of the measurement setup. Calibration target is the pitch angle α. The infrared laser (red dashed line) can be detected with the gap in the screen at distance *L* of the LiDAR. The visible laser (green solid line) is approximately parallel to the infrared laser, i.e. the angle *δα* and the offset *δh* are fixed during the measurements. The dotted black line is the view direction of the theodolite to the visible laser on the screen. The reference height h_0 is defined by the exit point of the laser beam at the centre of the lens.

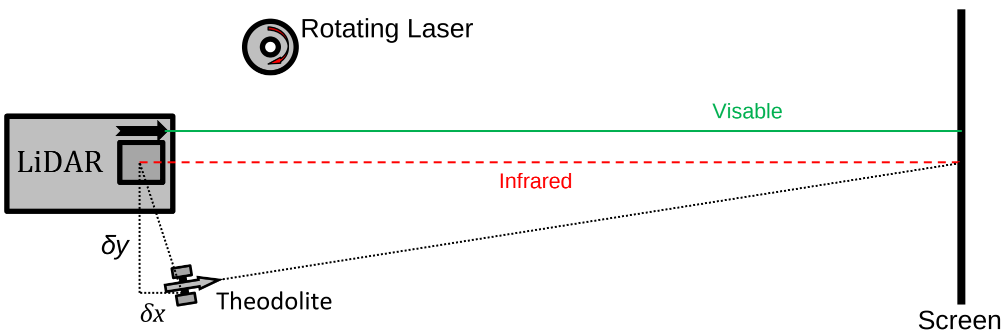

Figure 2: Top view of measurement setup. The rotating laser transfers the reference height h_0 from the LiDAR to the theodolite (Method A) and the screen (Method B). The longitudinal and transversal displacements of the theodolite, δ*x* and δ*y,* are components of the uncertainty budget of Method A.

Figure 3: Picture of the experimental setup. The inset shows the screen. It is constructed to identify the location of the infrared laser beam of the LiDAR. The white panels are moved up to the point at which they just do not block the laser. The rotating laser defines a reference height across the measurement site. Distance from LiDAR to the obstacle was around 83 m for all testes devices (slightly differing for each device).

Measurement Procedure

The measurements were performed with the following procedure:

I. Setup of the LiDAR:
   a. The visible laser is mounted on the scanning head.
   b. Depending on whether pitch or roll angles are calibrated select azimuth of scanning beam at 0° or 90°, respectively. Orient instrument with beam to screen.
   c. Set scan elevation to 0°.
   d. Adjust legs until both internal inclinometer (pitch and roll) are 0°.

II. Installation rotating laser at the height of the centre of LiDAR lens: The horizontal position of rotating laser is chosen to guarantee a free line of sight from the rotating laser to LiDAR, theodolite and screen.

III. Installation of theodolite:
   a. The theodolite is placed at approximately the same distance L from the screen as the lens of the LiDAR.
   b. The height of theodolite's reference mark is adjusted to h_0.

IV. Detection of invisible laser beam:
   a. The approximate location of the beam is identified by using an obstacle with a large area to block the beam. The beam is blocked if the CNR drops significantly at the distance of the screen.

b. The upper panel of the screen is moved downward until the beam is blocked. It is then slowly moved upward again until the beam is cleared. The panel is fixed in this position.
c. The same procedure is applied to the lower panel.
d. After upper and lower panel are fixed, the screen is kept in this position for the rest of the measurements.

V. Transfer of h_0 to the screen: The reference height level as given by the rotating laser is marked on the screen.

VI. The distance L to the scan head of the LiDAR is measured with the laser distance meter.

VII. The position of the infrared beam is measured:
a. The vertical position h of the infrared beam is given as the average of the positions of the upper edge of the lower panel and the lower edge of the upper panel.
b. The angle α of the infrared beam is measured with the theodolite by targeting the middle between the two panels.

VIII. The offset of the visible laser beam is measured:
a. The visible beam is adjusted to be close to the height of the invisible beam.
b. The offset δh between visible and infrared beam is measured.
c. The angle (α+δα) is measured by targeting the middle of the visible laser point on the screen. The offset angle δα is given as δα = (α+δα) – α.

IX. Measurement of additional angles:
a. The legs of the LiDAR are adjusted until the next wanted angle is given by the tested internal inclinometer. The not tested inclinometer is verified to be at 0°.
b. The distance ($h+\delta h$) between the middle of the visible laser on the screen and the reference level h_0 is measured. The vertical displacement h of the infrared beam is calculated by $h = (h+\delta h) - \delta h$.
c. The angle (α+δα) is measured by targeting the middle of the visible laser point on the screen. The inclination α of the infrared beam is calculated by α = (α +δα) – δ α.
d. Steps IX.a to IX.c are repeated until the complete angle range is covered.

X. Steps I to IX are repeated for the other inclinometer.

Measurement Uncertainty

The method used to estimate measurement uncertainty is based on reference [3]. The relation between distances and the elevation angle α is given by

$$\tan\alpha = \frac{h}{L} \tag{1}$$

From this the total uncertainty u of the angel α is derived to be

$$u^2 = u_\alpha^2 + c_h^2 u_h^2 + c_L^2 u_L^2 \tag{2}$$

with:

u_a uncertainty in angle measurement,

u_h uncertainty in measurement of vertical distances,

u_L uncertainty in measurement of horizontal distances

and the sensitivity factors

$$c_h = \frac{\partial\alpha}{\partial h} = \frac{L}{h^2 + L^2} \tag{3}$$

$$c_L = \frac{\partial \alpha}{\partial L} = -\frac{h}{h^2 + L^2} \qquad (4)$$

Formulas (3) and (4) are for angle measurements in radians. For measurements in degrees, the values have to be multiplied by (180°)/(π.). Table 1 summarises the measurement uncertainties.

Component	Description	Uncertainty Value
u_a	**Combined Uncertainty Angle α**	**0,029 °**
u_{a1}	Resolution Tested Inclinometer	0,029 °
u_L	**Combined Uncertainty Horizontal Distance *L***	**0,005 m**
u_{L2}	Distance LiDAR Reference Point - Screen	0,002 m
$u_{L2.1}$	Accuracy Laser Distance Meter	0,001 m
$u_{L2.2}$	Horizontality of Measurement	0,002 m
$u_{L2.3}$	Distance LiDAR-Front - Reference Point	0,005 m
u_h	**Combined Uncertainty Vertical Distance *h***	**0,03** m
u_{h1}	Definition of reference height h_0	0,02 m
$u_{h1.1}$	Accuracy Rotating Laser (Transmitter)	0,00013 m
$u_{h1.2}$	Accuracy Rotating Laser (Detector)	0,0006 m
$u_{h1.3}$	Definition of reference point on LiDAR	0,02 m
u_{h2}	Transfer h_0 to screen	0,0047 m
$u_{h2.1}$	Accuracy Rotating Laser (Transmitter)	0,00462 m
$u_{h2.2}$	Accuracy Rotating Laser (Detector)	0,0006 m
u_{h3}	Position Infrared Beam	0,01 m
$u_{h3.1}$	Positioning of upper panel	0,01 m
$u_{h3.2}$	Positioning of lower panel	0,01 m
$u_{h3.3}$	Position Infrared Beam	0,005 m
$u_{h3.4}$	Measurement Distance lower panel - h_0	0,005 m
u_{h4}	Position Visible Beam	0,02 m

Table 1: Assumed uncertainty components

Results

At this stage, calibration of four scanning LiDAR has been performed in the facilities of Deutsche Wind Guard. It turned out, that the inclinometers are more influenced by an offset than the slope factor. Results of all calibrations are listed in Table 2. Detailed results are shown in Figure 4 and Figure 5.

Device	Pitch Angle		Roll Angle	
	Slope	Offset	Slope	Offset
	[-]	[°]	[-]	[°]
Device 1	0,98	-0,13	-0,97	0,18
Device 2	1,02	-0,39	-0,99	0,03
Device 3	0,98	-0,07	-1,00	0,27
Device 4	1,03	-0,30	-0,99	0,05

Table 2: Results of calibrations performed at Deutsche WindGuard thus far

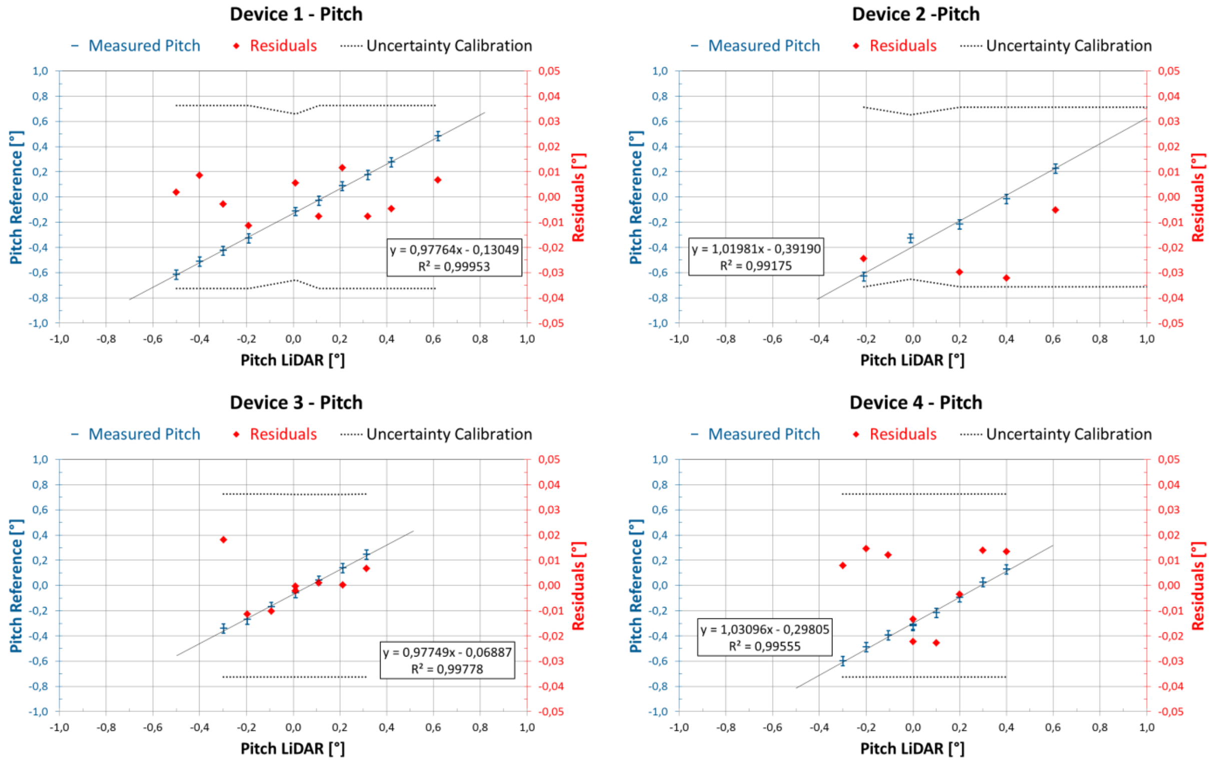

Figure 4: Calibration results of the pitch angle for tested units. Blue markers are the reference pitch as function of the pitch given by the LiDAR. The error bars denote the standard uncertainty. The red diamonds give the residuals, i.e. the deviation between the shown calibration line and the measured values. The dotted lines denote the standard uncertainty of the calibration on residuals the axis (k=2).

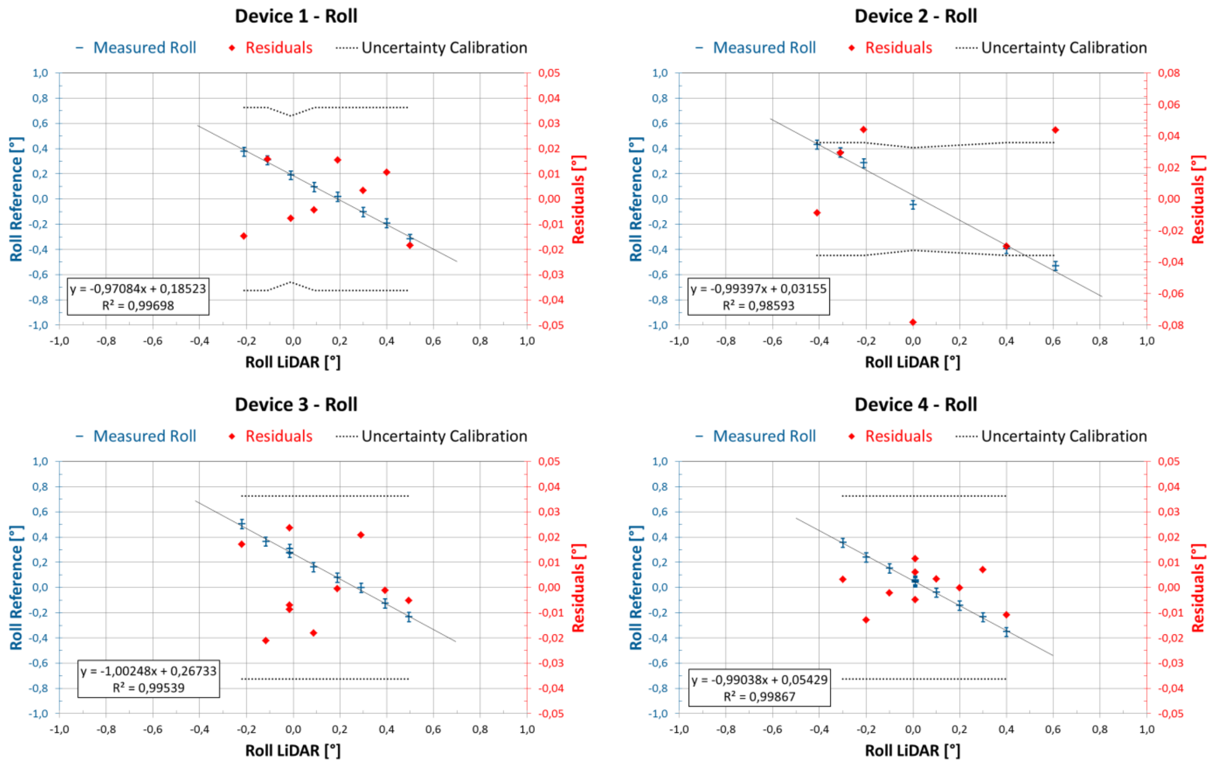

Figure 5: Calibration results of the roll angle of the LiDAR. Blue markers are the reference roll as function of the roll given by the LiDAR. The error bars denote the standard uncertainty. The red diamonds give the residuals, i.e. the deviation between the shown calibration line and the measured values. The dotted lines denote the standard uncertainty of the calibration on the axis of the residuals (k=2).

Conclusion

The results of devices tested thus far lead to the assumption that calibration of the built-in inclinometers is recommended to ensure a high accuracy in elevation angle and consequently in measurement height. For a typical measurement configuration for a power performance test of an offshore wind turbine, a deviation of the elevation angle of 0.1° will result in an error of measurement height of about 0.5 m. Taking the maximum offset of tested devices into consideration, an error in measurement height of about 2 m could occur. A height error that is unneglectable for power performance tests.

References

[1] IEC 61400-12-1 Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines, first edition 2005-12

[2] M. Courtney, "Calibrating nacelle lidars". *DTU Wind Energy E-0020*, January 2013

[3] ISO/IEC Guide 98-3:2008 Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)