Flywheel Calibration of Coherent Doppler Wind Lidar - Anno 2019

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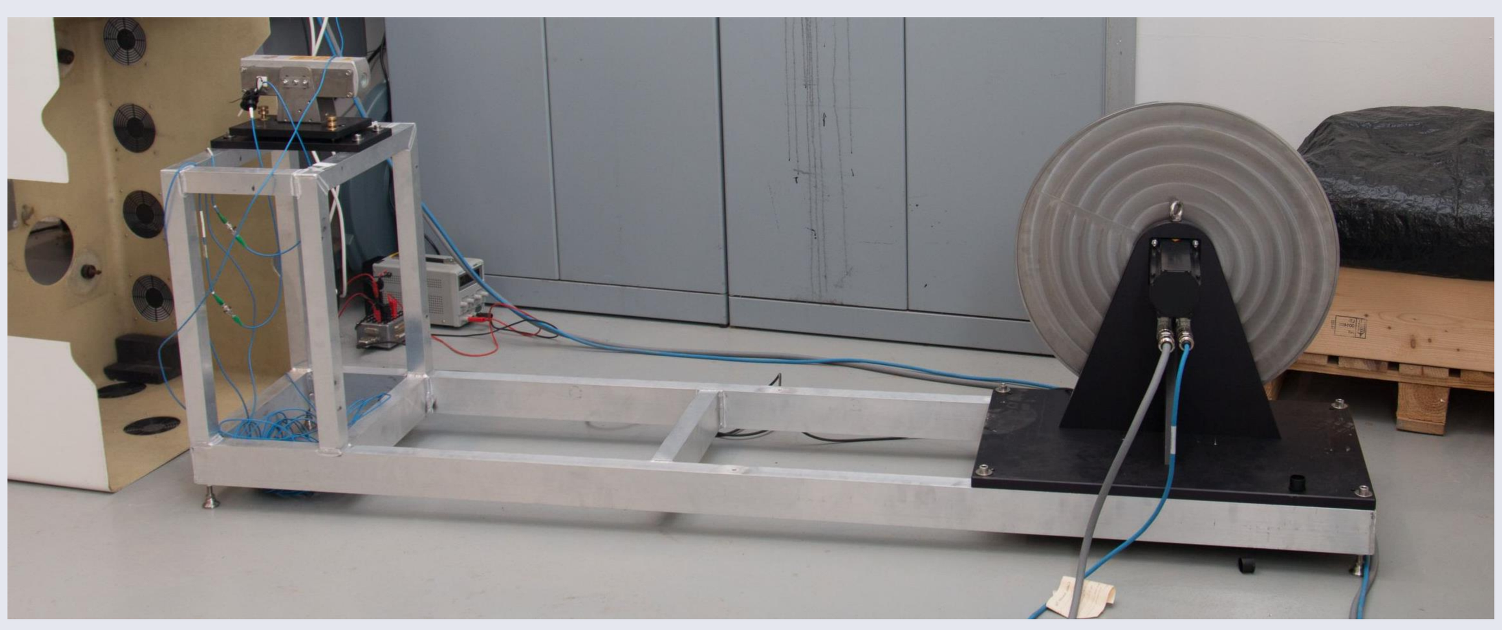
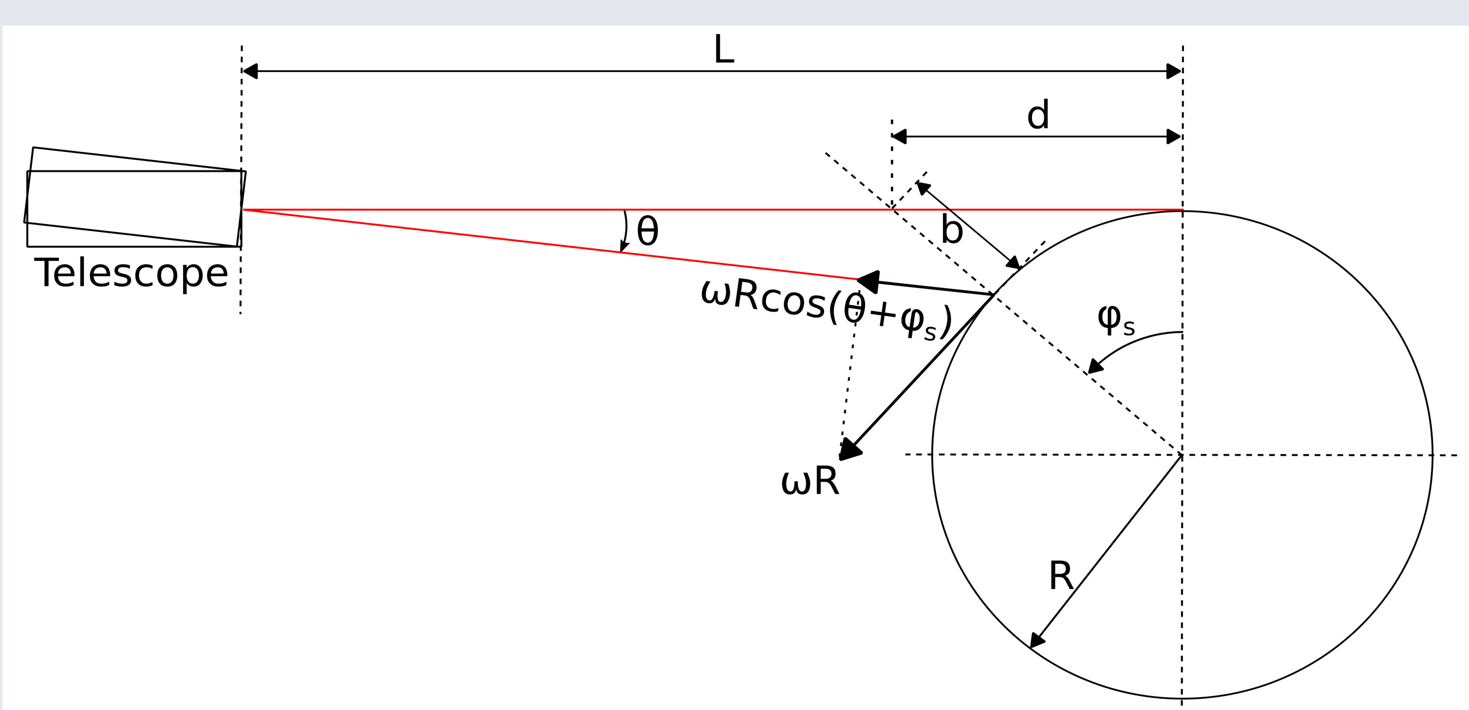
Motivation

"Lidars are absolute instruments" is a sentence often heard, and by that is meant, that given the laser wavelength and the sampling frequency, we are able to calculate the measured radial speed through the well-known equation: $V_r = \frac{1}{2}\lambda \cdot \Delta f$. There are no empirical constants that have to be found through a calibration as is the case for e.g. cups or even LDAs.

Why then do we claim that lidar calibration is necessary anyhow? Probably the most direct answer is that without a calibration we cannot know that the lidar is getting it right. There could be wrong constants or some subtle errors in the algorithm. Only by comparing to a known 'truth' can we be completely sure that the lidar gives the correct speed.

Calibration rig





- Stainless steel wheel: R = 286.76 mm
- Aluminium frame: L = 1.58 m
- Telescope: 1" aperture, f = 0.10 m
- Angular velocity measured by high resolution tachometer

Model

A simple model relating the error in measured speed due to non-tangential skimming angle, φ_s, to the inclination angle, θ, has been developed.

By assuming the laser beam is infinitely narrow and that θ and φ_s are both small, the relation between θ and φ_s can be found from simple geometrical considerations:

$$\varphi_s \approx \sin\varphi_s \approx \frac{d}{R} = \sqrt{\frac{2L\theta}{R}}$$

Now, the lidar only measures the speed component along the line-of-sight, thus

$$V_{Lidar} = V_{Wheel} \cdot \cos(\varphi_s + \theta) \approx V_{Wheel} \cdot \cos(\varphi_s),$$

and by Taylor expansion of the cosine term a simple expression for the speed ratio is reached

$$\frac{V_{Lidar}}{V_{Wheel}} \approx 1 - \frac{\varphi_s^2}{2} = 1 - \frac{L\theta}{R}.$$

Model – Thick beam

In reality the laser beam has a finite width and the lidar response must be found through

$$V_{Lidar} = \frac{1}{\phi_{s1} - \phi_{s0}} \int_{\phi_{s0}}^{\phi_{s1}} V_{Wheel} \cos(\phi + \theta) \mathrm{d}\phi \Leftrightarrow$$

$$\frac{V_{Lidar}}{V_{Wheel}} = \frac{1}{\phi_{s1} - \phi_{s0}} [\cos\theta (\sin\phi_{s1} - \sin\phi_{s0}) + \sin\theta(\cos\phi_{s1} - \cos\phi_{s0})],$$

which approaches the above approximation as the beam becomes narrower.

In the special case when part of the beam is skimming above the wheel and thus $\phi_{s0} = 0$

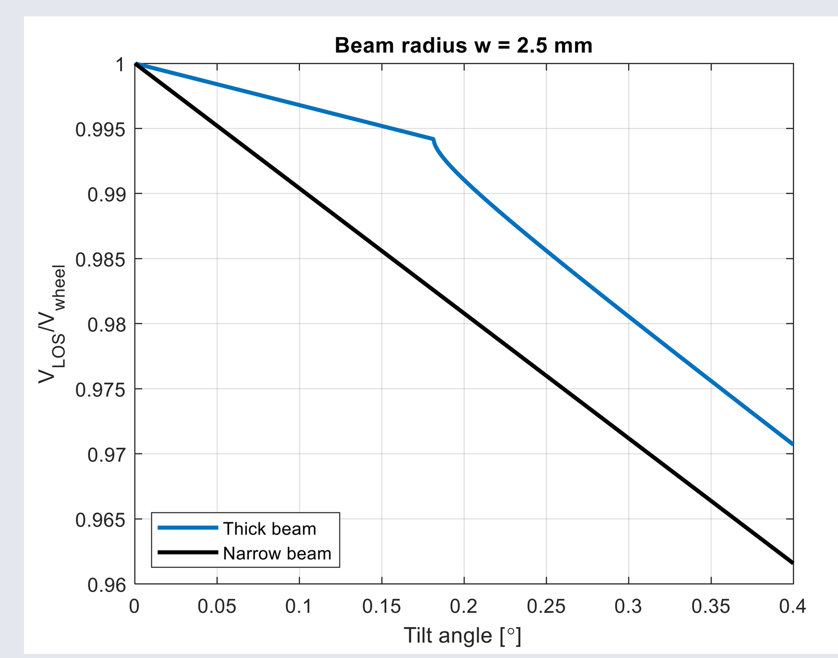
$$\frac{V_{Lidar}}{V_{Wheel}} \approx 1 - \frac{\varphi_s^2}{6} = 1 - \frac{L\theta}{3R}.$$

In this region the sensitivity to the tilt angle is thus reduced by a third.

Main uncertainty components

- Wheel diameter: 0.1 mm
  - Relative uncertainty $u_r = \frac{0.1\,mm}{287\,mm} = 3.5 \cdot 10^{-4}$
- Frequency from tachometer to speed conversion: 10 ppm
  - Relative uncertainty $u_\omega = 1 \cdot 10^{-5}$
- Tilt angle resolution: 0.01°
  - Relative uncertainty $u_{\Delta\theta} = \frac{L}{R} \cdot \frac{\Delta\theta}{2} \cdot \frac{1}{\sqrt{3}} = 2.8 \cdot 10^{-4}$
- Combined relative uncertainty $u_{ref} = \sqrt{u_r^2 + u_\omega^2 + u_{\Delta\theta}^2} = 4.5 \cdot 10^{-4}$

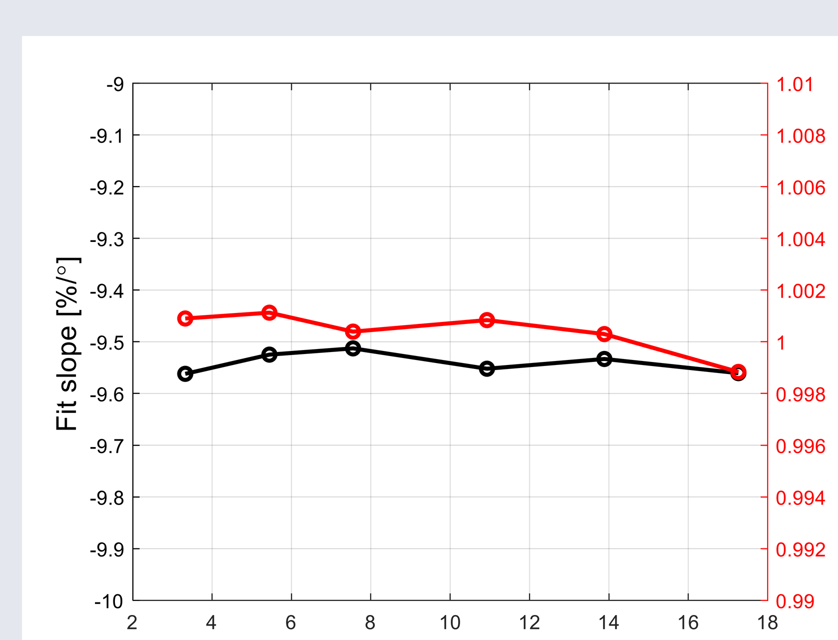
Simulations



Simulated measured lidar speed over reference wheel speed as function of tilt angle for an infinitely narrow beam and a beam of finite width. The reduced sensitivity to tilt is clearly seen and also that this leads to a shift towards larger angles in the region of higher sensitivity. Extrapolating from the high sensitivity region to $\theta = 0$ without compensating for the beam width will therefore lead to errors in the calibration.

Results

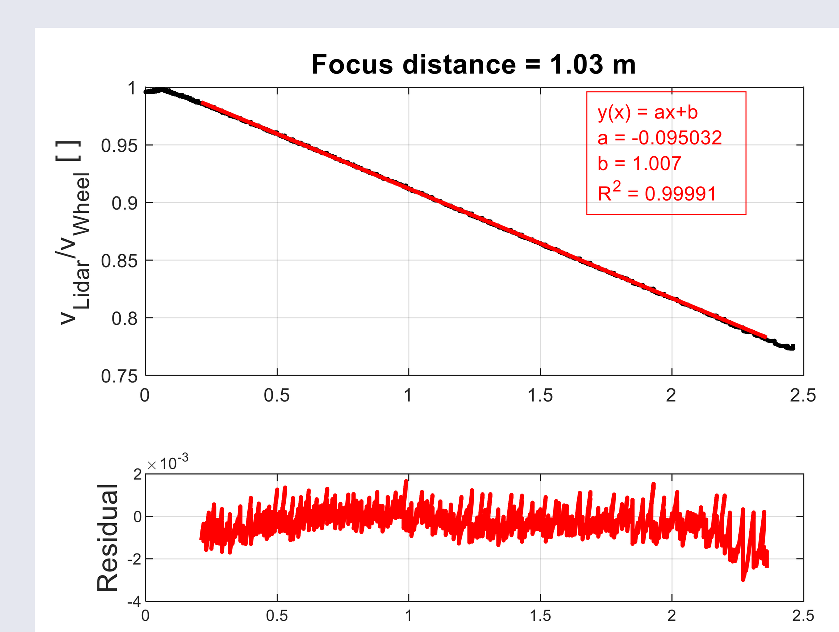
Function of speed

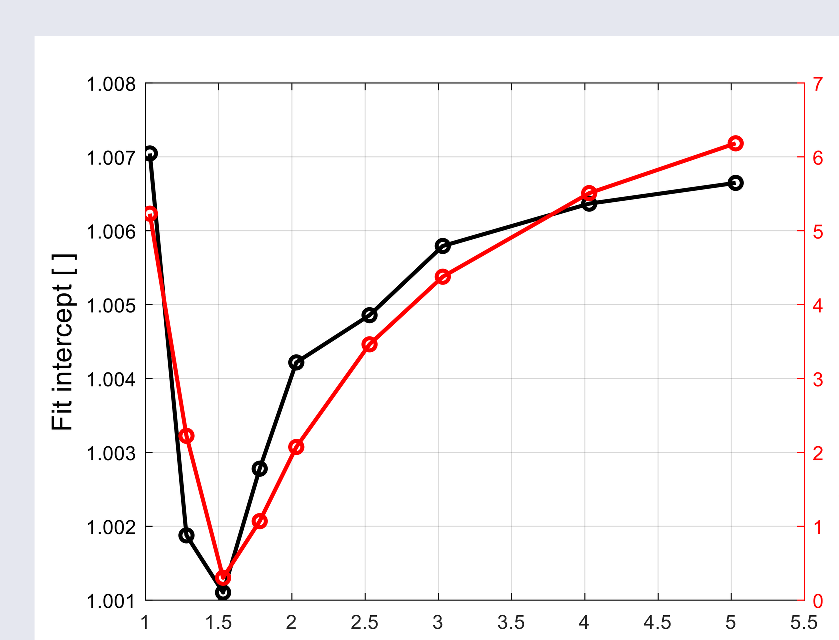


Top: Example of calibration measurement at 5.44 m/s reference speed together with affine fit (red). The beam is focused at the top of the wheel. Oscillations in the residual plots are due to the very narrow Doppler peak moving through the spectral bins alternatingly over- and underestimating the speed.

Bottom: Fit parameters (slope and intercept) as function of reference wheel speed

Function of focus distance





Top: Example of calibration measurement with laser beam focused at 1.03 m. The wheel speed is kept constant at 10.93 m/s.

Bottom: Fit intercept as function of focus distance together with the calculated beam width at the wheel. Best fit is found when the beam is focused close to the wheel and it is clear that the fit is influenced by the beam width emphasising the need to compensate for this.

Conclusions & Future work

- Calibration rig built and running
- Model for measurement error as function of inclination angle made
- Measurements agree well with model
- Method stable over wide range of speeds
- The main uncertainties have been identified but further work needed including wheel eccentricity
- The line-of-sight speed can be calibrated to an uncertainty of approximately 1.0‰
- Beam width compensation necessary

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