

Wind speed determination from a UV direct detection fringe imaging DWL prototype

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Abstract: The determination of the wind speed from direct detection Doppler Wind Lidar instruments is a crucial part within their development and operation. Our previously developed AEROLI system uses a fringe imaging, field widened Michelson interferometer as its spectral analyzer. To derive the wind speed information from the obtained measurand/raw data, a complex process of different operations (including multiple corrections and fitting operations) is necessary. In this work, we describe this process in detail, focusing on the influence of the distinct steps on the final outcome (wind speed dispersion, bias, correlation with reference DWL), including an investigation of the most promising steps for optimization. Further, a noise-floor method for the classification of the measurement quality without the need of a wind-speed reference (as DWL or anemometer) was applied to data from this UV direct detection DWL for the first time.

1. Introduction

The data processing for direct-detection Doppler Wind Lidar instruments is a complex task requiring a lot of distinct steps.

In this work, we investigated this process for a prototype UV direct detection Doppler Wind Lidar (termed AEROLI for its designated use in aeronautics' applications), which incorporates a fringe imaging field widened Michelson interferometer as a spectral analyzer, in detail [1]. Previous validation of the prototype was successful, but confined to just two ranges up to 100m, and with highly selected data, close to the ground [2, 3].

Our new dataset is based on a 14-month wind measurement campaign conducted in high-altitude at the environmental research station Schneefernerhaus (2650 m a.s.l.) at mount Zugspitze near Garmisch-Partenkirchen, Germany. Over this extended time period, measurement data could be taken under a wide range of atmospheric conditions, including seasonal differences, from snow to dust, calm and very turbulent conditions.

This dataset enabled us to validate the instrument's measurement capabilities under more realistic conditions beyond the first proof-of-concept several years ago, with first results having been published in [4].

2. Instrument

The UV direct detection Doppler Wind Lidar prototype AEROLI (**a**eronautics **l**idar) was developed for gust load alleviation on airplanes.

This specific measurement concept was selected to account for the aviation requirements of measurability under typical atmospheric conditions at flight level, which includes the possibility to encounter airmasses almost completely void of aerosols midflight. A direct detection UV DWL concept fulfils this requirement, as Rayleigh scattering from air molecules alone is sufficient for operation, with no need for additional presence of aerosols.

Our prototype uses a frequency tripled Nd:YAG Laser (355 nm, 100 Hz) and a Newtonian telescope with a 14 cm primary mirror for the receiver. The backscattered light is then coupled into an optical fiber, which has a square shaped core for beam forming and improved optical scrambling.

A monolithic fringe imaging field widened Michelson interferometer is used as a spectral analyzer, with an FSR of 10.6 GHz and is temperature compensated. The two-dimensional linear fringe (resulting from a slight skew of one of the interferometer mirrors) is compressed with a cylindrical lens and projected onto a 16-channel PMT-array detector.

The PMT-array's current signal is then amplified with a transimpedance amplifier (TIA) and the resulting voltage digitized with analog-to-digital converter cards at a sampling frequency of 31.25 MHz. For every laser pulse, the backscattering signal is saved up to a certain distance, thus leading to large data files (16 channels * 432 rangegates * 100 pulses/s). Timestamps for each trigger event (laser pulse) are recorded simultaneously.

3. Data evaluation workflow

The distinct steps of the data analysis can be seen in figure 1.

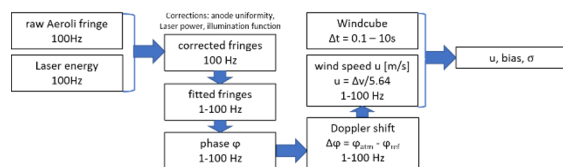


Figure 1. Data evaluation workflow

Raw data is corrected for anode uniformity of the PMT-array, then power corrected with internal power data from the laser. Then it is split into single pulses, which eases temporal averaging.

Those fringes, both for a direct laser reference pulse and from the atmospheric return, are then fitted with a modified cosine function to extract the phase information, which quantifies the Doppler shift (between reference Laser pulse and backscattered atmospheric signal) and thus the measured wind speed.

In comparison with a heterodyne-detection DWL (Leosphere Windcube[©] 200s), additional evaluation of bias and standard deviation is possible.

Temporal and spatial averaging, as well as the chosen reference rangegate influence the final result. Another important factor is the illumination function correction.

4. Illumination function

The opto-electronical instrument function (which we call illumination function) modulates the illumination (amplitude distribution) of the detector. As it is not a flat top distribution, the fringe gets distorted.

Hence an illumination function correction is necessary to obtain cosine shaped fringes for successful fitting and Doppler phase determination.

Fringe shapes for one rangegate (distance) are plotted over the 16 PMTA-detector channels in Figure 2. The corrected fringe (red) is shown, which was computed from the measured raw fringe (green) and the illumination function (blue).

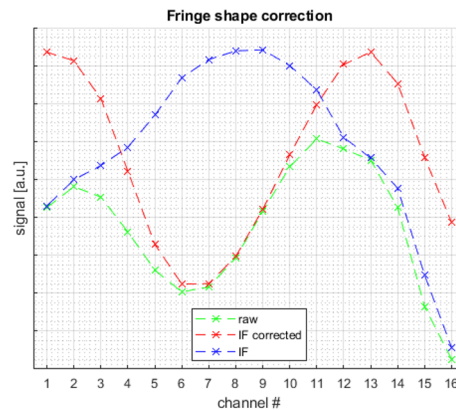


Figure 2. Fringe shape correction

It is obtained by changing the laser frequency to move the fringe maximum spatially over the interferometer's free spectral range (FSR), and thus over the detector. The envelope of the fringes from this procedure gives the illumination function for each rangegate. As the illumination function is range and time dependent, it differs between the rangegates for the reference and atmospheric signal.

Due to different variabilities with our DWL prototype, the illumination function yields a certain instability in time. This demands a determination of the illumination function consistently, in our case every several hours of wind speed measurement time.

5. Noise-floor-method

To estimate the performance of the AEROLI prototype without the need for a reference Lidar, we used the noise floor method as described in [5]. The underlying concept is Kolmogorov's description of atmospheric turbulence, following a slope of -5/3. This can be seen in the power spectral density (PSD) of measured atmospheric wind, assuming turbulence was present.

Beyond a certain frequency, the noise of the instrument is higher than the turbulence, thus inducing a characteristic change of the spectrum from slope to constant (see Figure 3). The value of the noise floor can be interpreted as the instrument noise induced best possible wind speed error.

6. Results

The results of such a noise floor analysis can be seen in Figure 3. On the left side of the spectrum, the data follows the $-5/3$ slope, but then the noise floor predominates. The here shown value of 0.39 m/s is remarkably low, as this measurement was taken during a period with extremely low aerosol content and thus a very weak backscatter signal. Earlier ground tests have shown a higher, but comparable error [2].

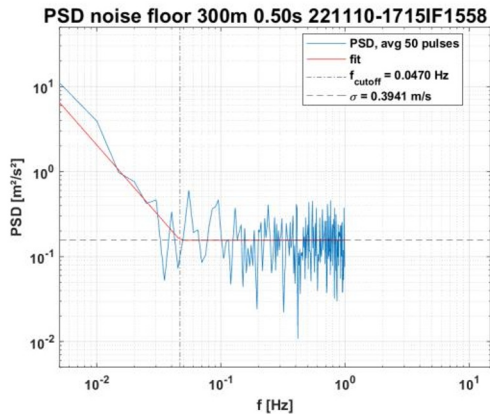


Figure 3. Noise floor of wind measurement

Another big influence on the results of the data evaluation is the illumination function. As during the measurement time of the illumination function there can be atmospheric disturbances at certain distances of the line of sight (we encountered snow, clouds and dust on our high-altitude campaign), signal intensity can vary a lot over baseline. This signal intensity increase would render the measured envelope at the affected distance useless.

To mitigate this effect, the temporal signal of each detector channel was fitted with a suitable function, which estimated the baseline efficiently to enable data evaluation even for these difficult conditions.

Comparing with a coherent IR DWL (Leosphere Windcube® 200s), the bias, standard deviation and Pearson correlation for the AEROLI system can be evaluated.

As the Windcube® Lidar is dependent on a sufficient atmospheric aerosol concentration for measurements, the clear air we encountered during the high-altitude campaign repeatedly posed a challenge for this device. Sometimes the signal was not sufficient at all, albeit using the highest accumulation times and range averaging settings available for the Windcube®.

Hence in Figure 4, the Windcube® accumulation time is 10 s with a range averaging of 100 m. The AEROLI time resolution is 0.5 s with a range averaging of 50 m.

The figure shows a comparison between windspeeds measured with the AEROLI (blue crosses) and Windcube (orange crosses) lidars (upper plot). The bias from the AEROLI measurement has a value of 8.0 m/s under the assumption the Windcube shows the absolute truth.

Same goes for the deviation between the two instruments (center plot), which shows 0.3 m/s for the AEROLI system, again assuming the Windcube® is measuring without error. When accounting for a Windcube® error bigger than zero in the same order of magnitude, the standard deviation of AEROLI is even lower. The bottom plot depicts the correlation between the two devices, with a high Pearson correlation coefficient of 0.92.

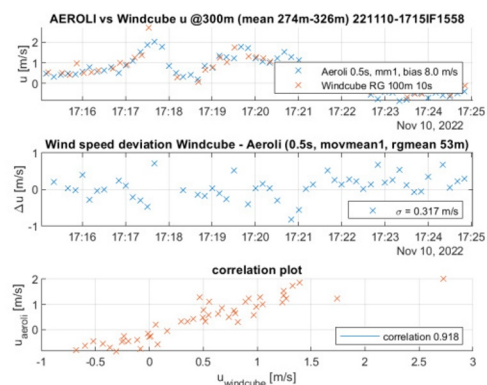


Figure 4. Windcube comparison

These first results show the capabilities of our AEROLI DWL prototype under more realistic atmospheric conditions than before, which further validates the eligibility for the intended use case as a gust load alleviation lidar for aeronautics.

7. References

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[4] P. Linsmayer, P. Vrancken, “Analyzing raw data measured by a UV direct detection Doppler Wind Lidar comprising a Fringe Imaging Michelson Interferometer: challenges and limitations”, European Lidar conference, Cluj-Napoca, 2023.

[5] A. Dolfi-Bouteyre et al., “Long-range wind monitoring in real time with optimized coherent lidar”, *Opt. Eng.*, 56(3), 031217, 2016.