Challenges in noise removal from Doppler spectra acquired by a continuous-wave lidar

Angelou, Nikolas; Foroughi Abari, Farzad; Mann, Jakob; Mikkelsen, Torben Krogh; Sjöholm, Mikael

Published in:
Proceedings of the 26th International Laser Radar Conference

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Angelou, N., Foroughi Abari, F., Mann, J., Mikkelsen, T., & Sjöholm, M. (2012). Challenges in noise removal from Doppler spectra acquired by a continuous-wave lidar. In Proceedings of the 26th International Laser Radar Conference: Session 5P: Atmospheric winds - turbulence [S5P-01]

CHALLENGES IN NOISE REMOVAL FROM DOPPLER SPECTRA ACQUIRED BY A CONTINUOUS-WAVE LIDAR

Nikolas Angelou, Farzad Foroughi Abari, Jakob Mann, Torben Mikkelsen, Mikael Sjöholm

Department of Wind Energy, Technical University of Denmark, Risø Campus, Frederiksborgvej 399, DK 4000 Roskilde (Denmark), E-mail:nang@dtu.dk, fzfa@dtu.dk, jmsq@dtu.dk, tomi@dtu.dk, misj@dtu.dk

ABSTRACT

This paper is focused on the required post processing of Doppler spectra, acquired from a continuous-wave coherent lidar at high sampling rates (400 Hz) and under rapid scanning of the laser beam. In particular, the necessary steps followed for extracting the wind speed from such Doppler spectra are presented. A method for determining the background noise spectrum without interrupting the transmission of the laser beam is described. Moreover, the dependency between the determination of the threshold of a Doppler spectrum with low signal-to-noise ratios and the characteristics of the wind flow are investigated and a systematic approach for removing the noise is outlined. The suggested post processing procedures are applied to two sample time series acquired by a short-range WindScanner during one second each.

1. INTRODUCTION

Ground based laser radar measurements of the wind in the atmospheric boundary layer have been around for some decades Fyjii & Fukuchi [2005]. Recently they have been started to be routinely used in the wind energy industry for resource assessment through the implementation of the Velocity Azimuth Display (VAD) technique for retrieving the mean horizontal wind profile Emeis et al. [2007]. This technique relies on an assumption of homogeneity of the wind flow over the scanned area, which, however, breaks down in complex flows.

In order to address this issue, the former Risø National Laboratory for Sustainable Energy, now known as the Department of Wind Energy at the Technical University of Denmark (DTU), is developing the method of using three coordinated continuous-wave (cw) coherent Doppler laser radars with steerable beams for measurements of the 3D wind and turbulence field in complex terrains and complex flows in the vicinity of wind turbines, buildings, and escarpments Mikkelsen et al. [2008].

The DTU short-range (10 m - 150 m) WindScanner is based on a modified commercially available ZephIR cw coherent wind lidar operating at the wavelength of 1.5 μm Karlsson et al. [2000], developed by QinetiQ and manufactured by Natural Power. The modified version can stream out averaged Doppler spectra at rates of up to about 400 Hz and it is equipped with an acousto-optic modulator (AOM), which provides the possibility to measure the sign of the Doppler shift. Although the short averaging time allows the measurement of high-frequency turbulent fluctuations of the wind speed, it produces spectra with higher variance in the spectral estimation. Thus, it is necessary to alleviate the background spectral noise in each individual estimated spectra prior to the application of a frequency estimator for determining the corresponding Doppler shift. In this study the influence of the proper spectral normalization, thresholding and Doppler shift frequency estimation is investigated.

2. ANALYSIS

2.1. Doppler Spectrum

The short-range WindScanner data acquisition unit has a sampling rate of 100 MHz and applies a 512-point Discrete Fourier Transform (DFT) to create one laser Doppler spectrum. Subsequently a number of these spectra are averaged in order to reduce the variations of the spectral noise and produce a Doppler spectrum where the Doppler shift could be estimated more accurately. The minimum number of spectra to be averaged is 500 corresponding to a streaming rate of approximately 400 Hz. Each Doppler spectrum, in the form of a one-sided spectrum, is represented in 256 frequency bins, with a spectral resolution of 0.195 MHz corresponding to 0.152 ms^{-1} per bin. By employing a AOM, the Doppler frequency shift corresponding to a wind speed of 0 ms^{-1} is shifted by 27 MHz, corresponding to the frequency bin 139. The first 10 bins of a spectrum are zeroed out due to the presence of the laser's inherent RIN noise. An example of a spectrum acquired from the short range WindScanner is presented in the Figure 1.

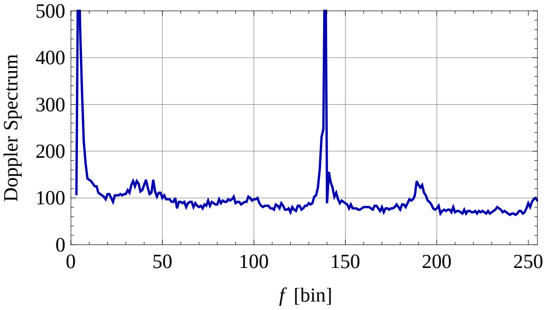

Figure 1: An example of a Doppler spectrum obtained from averaging 500 spectra obtained in 2.5 ms seconds.

The low spectral peaks appearing between the frequency bins 180 and 200 represent the Doppler shift due to wind while spikes appearing in the first 10 bins as well as around bin 139, are due to RIN noise and oscillator noise leakage around the 27 MHz, respectively.

2.2. Spectrum normalization

The standard approach to obtain the background spectrum used for flattening the Doppler spectra is to close the laser beam shutter and calculate the spectrum from the corresponding detector signals. However, under some circumstances during the operation of the short-range WindScanner, fluctuations in the spectral values in the frequency area around the AOM frequency, i.e., 27 MHz, were observed. This can result in a reduced resolution of the minimum detectable radial wind speed, due to overestimation of the background noise.

Therefore, an approach to model the background noise spectrum for each individual measured spectrum was implemented. The concept takes advantage of the rapid scanning of the coherent laser beam. The steering of the laser beam in different directions results in the variation of the projection of the wind speed to the line-of-sight of the laser beam and thus altering the magnitude of the detected wind speed. In that context, a good estimate of the true background spectrum was approached through the calculation of the median value per frequency bin of the Doppler spectra acquired over a long period.

Two typical background spectra obtained from the median values of spectra acquired over 60 seconds are presented in Figure 2. The two background spectra correspond to data sets acquired in different turbulent wind conditions.

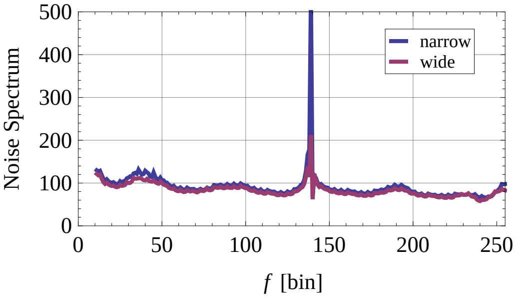

Figure 2: A background spectrum obtained from 60 seconds for two data sets with different Doppler spectra characteristics (blue: narrow Doppler spectra and purple: wide Doppler spectra).

2.3. Threshold estimation

Following the noise flattening it is necessary to determine a threshold level value which defines the limit, above which a Doppler spectrum is considered to be caused by the wind speed. In Figures 7 and 8 two sample spectra corresponding to different wind fluctuations (turbulent wind - wide spectrum and non-turbulent wind - narrow spectrum, respectively) after flattening the noise are presented. It can be observed that the measured wind Doppler spectra are characterized by high spectral variance. Therefore, the determination of the correct threshold is essential in order to remove the spectral noise fluctuations. Usually the calculation of the threshold is based on the mean value (μ) plus a number of standard deviation (σ) of the Doppler spectrum in a frequency range where no wind speed signals are anticipated.

Due to the non-existence of a reference sensor, providing wind speed data at the sampling rates of 400 Hz, a validation of the determination of the appropriate threshold is attempted by calculating the mean of the absolute differences between consecutive values of the wind speed retrieved using the median frequency estimator. For each of the two cases presented above, a non-integer incrementation of the number of standard deviations added to the mean was carried out, in the interval between 0 and 5 in steps of 0.1. In both cases, the same tendency is observed where the mean absolute difference is reaching a minimum and subsequently increases almost exponentially, as a function of the number of standard deviations added to the mean for the definition of the threshold, as can be seen in Figures 3 and 4.

The suggested number of standard deviations is not the same for the two data sets, indicating that a systematic approach for the determination of the threshold should take into account the shape of the Doppler spectra relative to the variations of the spectral noise level.

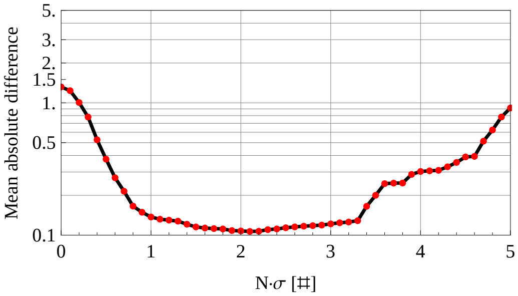

Figure 3: Mean absolute difference of consecutive wind speeds vs. spectra threshold level in the case of a data set with narrow spectra.

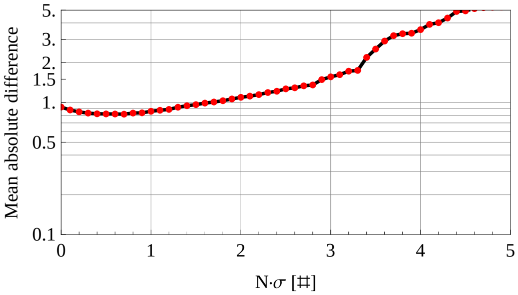

Figure 4: Mean absolute difference of consecutive wind speeds vs. spectra threshold level in the case of a data set with wide spectra.

2.4. Doppler shift frequency estimators

So far, during the analysis of the Doppler spectra acquired by a short range WindScanner, three different methods

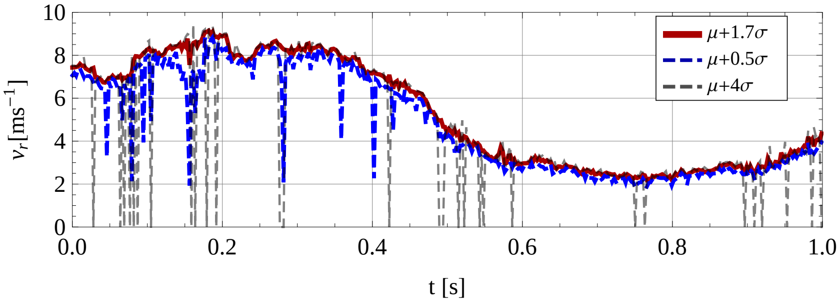

Figure 5: Time series (∼400 Hz) of the radial wind speed calculated using *med* frequency estimator over a set of narrow Doppler spectra.

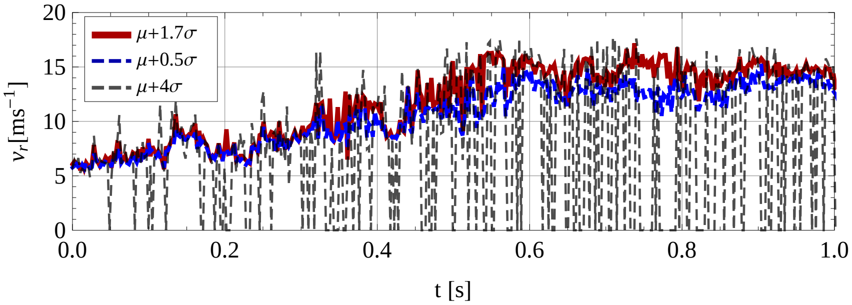

Figure 6: Time series (∼400 Hz) of the radial wind speed calculated using *med* frequency estimator over a set of wide Doppler spectra.

for estimating the corresponding Doppler shift have been tested. The first is based on the location of the maximum value of the Doppler spectrum (denoted as *max*), the second is based on a centroid function (denoted as *cen*), and the third is based on the location of the median value of the Doppler spectrum (denoted as *med*).

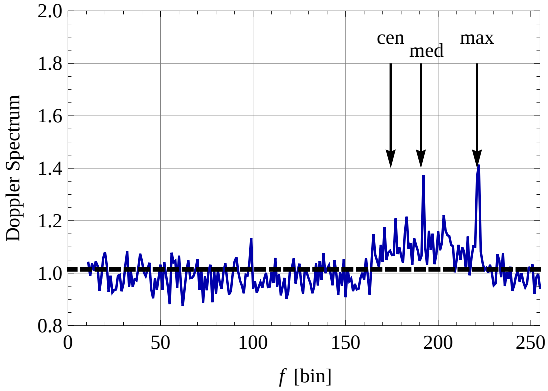

Figure 7: Example of a wide spectrum found in the time series presented in Figure 6.

It is observed that the *max* method is close to the *med* in the event of a narrow spectrum, as seen in Figure 8. However, in the case of a wide spectrum the maximum value of the Doppler spectrum does not necessarily correspond to the most representative wind speed Doppler frequency shift shown in Figure 7.

Moreover, in both spectra presented in Figures 7 and 8 the *cen* appears to deviate significantly from the frequency region were most of the Doppler energy is observed. This can be attributed to the influence of the frequency estimator's inabbility to fully threshold the noise spikes. Therefore, the *med* method, being more stable and less subject to noise presence than the *max* and *cen*, is selected as the Doppler frequency estimator of choice during the analysis of the data acquired by a short-range WindScanner.

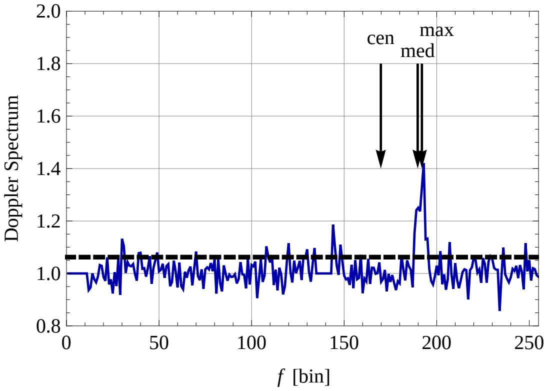

Figure 8: Example of a narrow spectrum found in the time series presented in Figure 5.

3. WIND SPEED TIME SERIES

3.1. Different threshold levels

Wind speed time series corresponding to measurements acquired over one second are presented in Figures 5 and 6. The wind speeds were calculated based on the application of the *med* frequency estimator over the complete Doppler spectra for three different values of the threshold.

Two different levels of the threshold were defined by the corresponding number of standard deviations where the minimum absolute difference in Figures 3 and 4 was observed. Moreover, one more threshold level was selected where both time series present relatively large differences between consecutive estimated wind speed values.

In both cases the selection of a large threshold level $(\mu + 4\sigma)$ may lead to the removal of the whole Doppler spectrum resulting in wind speeds equal to 0 ms^{-1} (blank spectra). On the other hand, there are cases where the overestimation of the threshold is removing low intensity fluctuations and subsequently pushes the median estimation of the Doppler spectrum away from the true wind speed. Furthermore, the over-thresholding is more detrimental in the case of wide Doppler spectra in comparison to the case of narrow Doppler spectra. Thus, the resultant velocity time series exhibits more drastic variations (e.g., notches) as shown in Figure 6.

4. DISCUSSION AND CONCLUSIONS

In this paper the first measured wind speed time series acquired at 400 Hz from a short-range WindScanner is presented. A method for characterizing the background noise spectrum is described, which offers the possibility to take into account the variations of the noise close to the AOM frequency, i.e. 27 MHz, where the zero Doppler frequency is represented. The major advantage of this method is that it provides the possibility of estimating the background noise spectrum without interrupting the operation of the short-range WindScanner.

Prior to the frequency estimation, it is necessary to apply an appropriate thresholding of the spectra. It has been observed that no universal definition of the threshold is appropriate for the different applications, which calls for further investigations in order to refine the method for estimation of the threshold level.

Although it has been shown that the median frequency estimator is more stable and trustworthy than the centroid and maximum frequency estimators, there might still be more to gain in a further study by applying for instance the maximum likelihood (ML) or minimum mean square error (mmse) estimators.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge Per Hansen, and Kasper Hjorth Hansen for their technical support. This study has been conducted as part of the new Danish research infrastructure facility activities of Windscanner.dk (http://www.windscanner.dk/).

REFERENCES

Emeis, S., Harris, M., & Banta, R. M. 2007, Meteorol. Z., 16, 337

Fyjii, T. & Fukuchi, T. 2005, Laser Remote Sensing (Taylor & Francis)

Karlsson, C., Olsson, F., Letalick, D., & Harris, M. 2000, Applied Optics, 39, 3716

Mikkelsen, T., Mann, J., Courtney, M., & Sjöholm, M. 2008, in IOP Conference Series: Earth and Environmental Science, ISARS, 148–156