Application of 2D Deconvolution Algorithms to Correct the Chirp-Induced Velocity Bias in Atmospheric Wind-LIDAR Datasets

Johannes Bühl, Ronny Engelmann, Albert Ansmann
Leibniz Institute for Tropospheric Research
Permoserstr. 15, 04315 Leipzig, Germany
johannes.buehl@tropos.de

1. Introduction

In the last decades coherent Doppler wind LIDARs have proved to be important tools for the measurement of atmospheric wind velocities [1]. They detect the relativistic Doppler shift in the light scattered back from particles within the atmosphere. Measurement accuracies in radial velocity <0.1 m/s can be accomplished. To reach this accuracy the influences of many factors have to be taken into account. Examples are the pointing accuracy, the laser frequency stability and the chirp of the laser pulse. The first two factors shift the measured wind speed by a constant factor. However, the measurement error induced by the laser chirp is more complex.
In this work we want to present a technique to simulate and to correct the error induced by the laser pulse chirp. We use 2D deconvolution algorithms known for example from astronomical image enhancement.

2. Theoretical Background

2.1 System Overview

The Doppler lidar system used in this experiment is described in detail in [2]. Yet we want to give a brief overview.
We use a wind LIDAR with a Master-Oscillator-Power-Amplifier (MOPA) laser design operating at a wavelength of 2022 nm. The bandwidth of the master laser is 150 kHz. The pulse energy is 2 mJ and the pulse length is about 500 ns. A frequency chirp of about 1 MHz/µs is measured. The frequency of the pulse is shifted by -80MHz with respect to the master laser by an acousto-optical modulator. The pulse repetition rate is 750 Hz.
While the laser pulse is being emitted by the power amplifier a part of the pulse is fed into a reference detector, superposed with the light of the master laser and the generated heterodyne signal is recorded with 250 Ms/s. The light scattered backward from atmospheric particles/aerosols is detected on another heterodyne detector. The two receivers use photodiodes of the same type, have similar amplifiers and their signals are recorded consecutively by the same data acquisition system. This is very important for the following analysis.

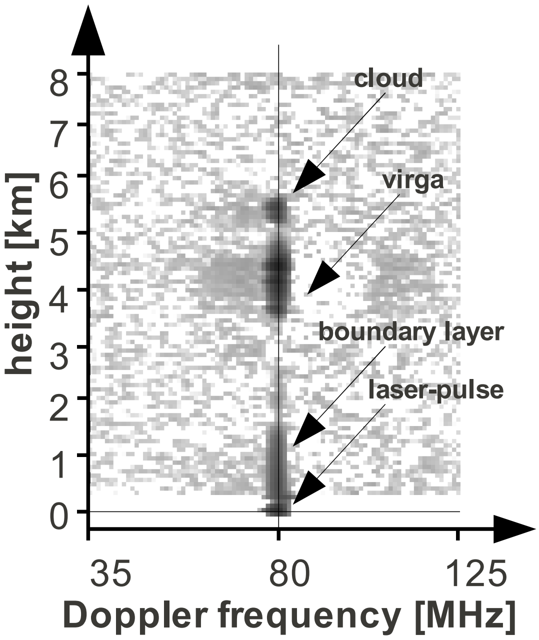

Figure 1: Plot of the averaged atmospheric Doppler spectra calculated for each height bin with an FFT.

2.2 Signal analysis

The heterodyne signal is recorded for 100 µs after the release of the laser pulse which corresponds to a distance of 15km in the atmosphere. In the context of this work the LIDAR always points vertically so the distance corresponds directly to the height above ground. For one laser shot the data acquisition system records 25000 data points which are immediately sliced into 200 bins of 250 data points (overlap of 125 data points between the bins). On each slice a Fast-Fourier-Transform (FFT) is performed. The amplitudes of the complex values are calculated for each slice and stored in the memory. This is done for every emitted pulse. After two seconds the

amplitudes are averaged and stored on the hard disk. This approach greatly reduces the amount of data to be stored but of course prohibits any re-analysis of the raw heterodyne signal.
The further analysis is done by an independent computer program which searches for the peak within the averaged spectra. From there it calculates the wind velocity in each slice by the formula

$$v(n) = 2\ (fs(n) - fp)\ /\ \lambda. \qquad (1)$$

With
fs(n) : spectral peak frequency in n-th slice
fp : spectral peak of emitted laser pulse
λ : wavelength of the laser (2022nm)

Eq. (1) indicates that a Doppler shift of about 1 MHz corresponds to a vertical wind velocity of about 1 m/s. In Fig. 1 a dataset averaged over 2s is depicted.

2.3 Influence of the laser pulse chirp on the velocity measurement

To analyse the influence of the laser pulse chirp on the measured wind velocities we use a very simple model of the signal generation which is in full analogy to the image formation in optical devices like microscopes or telescopes.
For the measurement system described here a scattering particle within the atmosphere (dust particle, aerosol particle, cloud droplet...) is characterised by three parameters:

- The amount of light backscattered by the particle: *βp*
- The frequency shift of the light returned: *fp*
- The distance of the particle to the detection system. In our case this corresponds to the height above ground of the particle: *hp*

The laser emits a pulse with a certain bandwidth (in our case about 1 MHz). This pulse can be represented by a two-dimensional function *P(h , f)* (with *h*: height and *f*: frequency) and corresponds to the point spread function in two dimensional image formation. All frequency components of the laser pulse are Doppler shifted by the same value, so the signal returned from a scattering particle within the atmosphere can be calculated by convolution of the reference pulse with a delta function at the position *(hp , fp)* multiplied by the backscatter coefficient *βp*. Since we are only investigating the influence of the chirp in the frequency domain, amplitudes play a minor role and we can set *β=0*. The Signal *S(h , f)* recorded by the system can thus be calculated by

$$S(h, f) = B(h, f) \otimes P(h, f). \qquad (2)$$

Here *B(h , f)* is a function containing the positions of the backscattering particles in the *(h , f)*-space and ⊗ denotes the two-dimensional convolution operation.
In our system we record the laser pulse 1μs before and after the pulse peak with a detector similar to the one used for atmospheric detection (same photodiode, same frequency response etc...). Therefore no further analysis of the detection system is needed and all the detection characteristics are simply measured and contained in the point spread function *P(h , f)* at the beginning of the dataset (see Fig. 1).
To determine the influence of the laser pulse chirp on the measurement of wind velocities we build a simple model of an atmospheric signal, which is depicted in Fig. 2a. It simulates

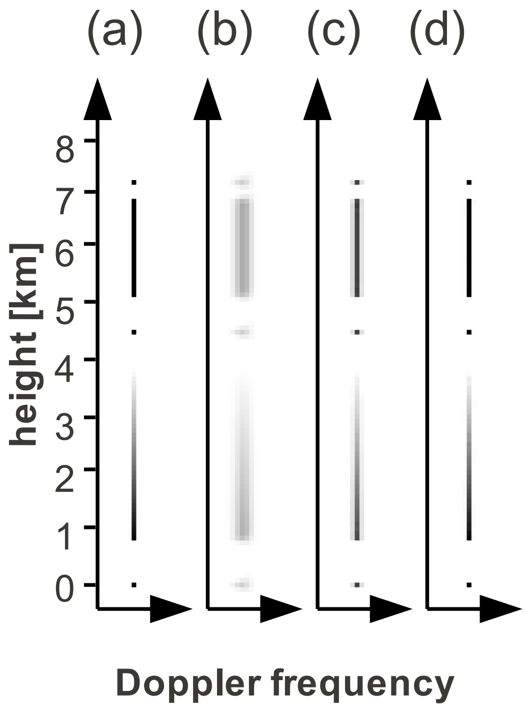

Figure 2: Simulation of an atmospheric signal comparable to the real signal depicted in Fig. 1: (a) ideal input data (b) simulated signal (c) deconvolved (5 iterations) (d) deconvolved (10 iterations)

the reference pulse, the planetary boundary layer filled with aerosol, a cumulus-cloud and above a virga underneath a cirrus cloud. All signals are centred on the $f = 80$ MHz bin, where also the reference pulse is centred. That means that the radial velocity is zero for each height bin. The convolution of the simulated signal with a previously recorded (real) laser pulse is calculated and depicted in Fig. 2b. It is clearly visible that the strong delta-function-like signal of the cumulus and cirrus clouds return a copy of the laser pulse and the continuous signals in the boundary layer and in the virga are smeared.
In the next step we let the signal evaluation program analyse this dataset. The result is shown in Fig. 3 (solid line). Although there was no relative frequency shift included in the simulated dataset, vertical velocities of up to -1.6 m/s are detected. The chirp effect is especially prominent at the cloud bases and tops, but also in the continuous signals of the boundary layer and the virga. There the asymmetric shape of the laser pulse has shifted the signals by a constant factor of about -0.20 m/s. This bias was also observed during real atmospheric measurements.

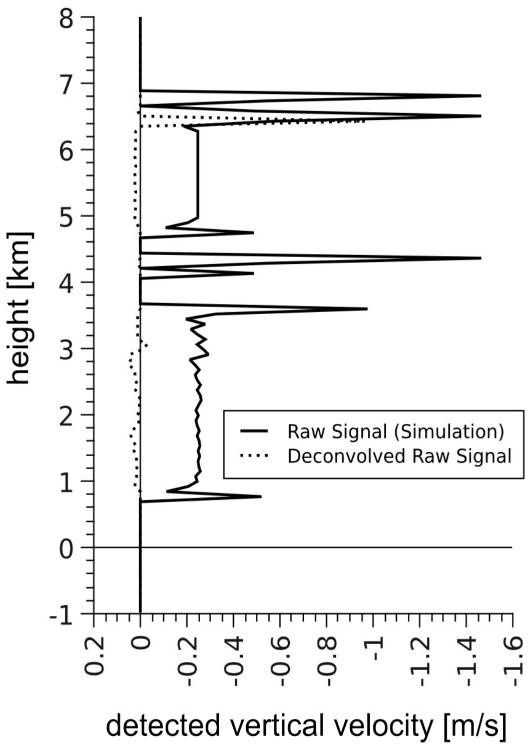

Figure 3: Detected vertical velocity in the the simulated signal before (solid line) and after (dotted line) deconvolution.

3. Correction of the chirp effect by 2D Deconvolution

With the analogy to two-dimensional image formation formulated in Section 2.3 we now can use deconvolution algorithms originally developed for telescopic and microscopic image enhancement. In our case we use the implementation of the Richardson-Lucy (RL) algorithm [3] of the image-restoration library “BiaQIm” [4]. This algorithm was applied to correct blurred images in the early days of the the Hubble Space Telescope. But there exist various other commercial and non-commercial programs, libraries etc. for image restoration which can be applied here.
The RL algorithm is an iterative algorithm which tries to reproduce the function $B(h, f)$ in Eq. (2) by making an initial guess and then convolve this guess with the given point spread function $P(h, f)$. The resulting two-dimensional dataset is subtracted from the original dataset $S(h, f)$. The difference (residual) is then used in the next iteration step to improve the guess of $B(h, f)$. The iteration is stopped after a defined number of steps or when the residual has become small enough.
The application of the RL algorithm on the simulated dataset of Fig. 2b is shown in Fig. 2c and 2d for 5 iterations (c) and 10 iterations (d). (Here the algorithm works exceptionally well because there is no noise included.)
Fig. 3 shows the evaluation of the signal deconvolved with 5 iterations (Fig 2c) as a dotted line. It is visible that after the deconvolution the continuous signals are shifted back to zero velocity. There are still some deviations present, especially around the upper cloud peak. This could probably be removed by further iteration steps but also by simply considering a signal threshold because the absolute signal intensity at this position is very low compared to the cloud peak itself (see Fig. 2c).

4. Application to real atmospheric data

Fig. 4 shows the result of the application of the RL algorithm on the atmospheric measurement of Fig. 1 with the same configuration as in the simulation of Section 3 with 10 iteration steps. It is clearly visible that like in the simulation, the cloud spectra are reduced to nearly one point. The comparison between the vertical-wind velocities calculated by the evaluation program before and after deconvolution are shown in Fig. 5.

Around the strong signals in the boundary layer and within the virga now white spaces are visible, which indicate that in this region the algorithm did not find any signal because the residual was too small or negative.

5. Conclusion

In this work we showed that it is possible to correct the chirp-induced bias in atmospheric wind measurements with a two-dimensional deconvolution of the dataset with its measured point spread function (which represents the chirped laser-pulse).

By interpreting the frequency-height dataset as a two-dimensional image and using an analogy to image formation theory, we can profit from the highly developed algorithms for image enhancement and -restoration.

We showed that it is easy to apply existing algorithms on atmospheric measurements to correct them for the chirp-induced frequency bias. As a positive side effect, also the range resolution and the frequency resolution of the signal increase. Those effects and the artefacts introduced by the deconvolution process will be subject of further study.

6. References

[1] S. Henderson, P. Gatt, D. Rees, and R. M. Huffaker, “Wind Lidar,” in *Laser Remote Sensing*, T. Fujii and T. Fukuchi, eds (CRC Press, 2005), pp. 469-722.

[2] Engelmann et al., 2008: Lidar observations of the vertical aerosol flux in the planetary boundary layer. *J. Atmos. Oceanic Technol.*, 25, 1296–1306.

[3] W. Richardson, "Bayesian-Based Iterative Method of Image Restoration," *J. Opt. Soc. Am.* 62, 55-59 (1972).

[4] P. J. Tadorous, “BiaQIm” (Software), URL: http://www.deconvolve.net/bialith/

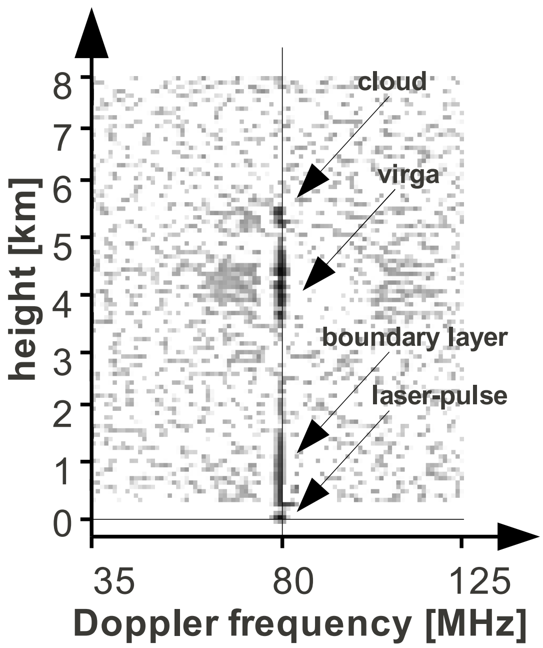

Figure 4: Plot of the atmospheric signal after the 2D deconvolution.

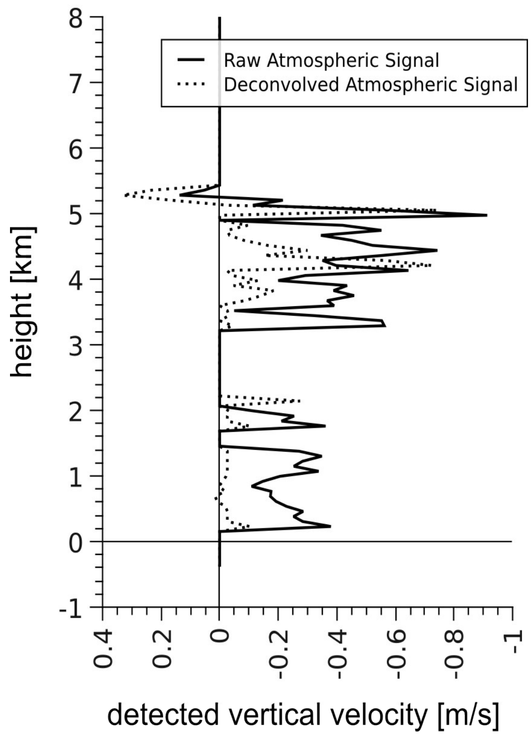

Figure 5: Detected vertical velocity in the the atmospheric signal (Fig. 4) before (solid line) and after (dotted line) deconvolution.