Airborne Coherent Doppler Wind Lidar measurements of vertical and horizontal wind speeds for the investigation of gravity waves

Benjamin Witschas, Stephan Rahm, Johannes Wagner, Andreas Dörnbrack
DLR, Institute of Atmospheric Physics, Oberpfaffenhofen, Germany
Benjamin.Witschas@dlr.de

Abstract: Gravity waves are well known phenomena in the atmosphere, but there is still a lack of knowledge of their life cycle including excitation, propagation and dissipation mechanisms. In order to investigate these topics, DLR's coherent Doppler wind lidar system was recently deployed during 3 airborne campaigns on the Falcon F20 research aircraft, namely the GW-LCYCLE I campaign (Kiruna, Sweden, December 2013), the DEEPWAVE campaign (Christchurch, New Zealand, June/July 2014) and the GW-LCYCLE II campaign (Kiruna, Sweden, January/February 2016).
In this paper, a case study based on a research flight performed during GW-LCYCLE I is discussed and a method for correcting horizontal wind contribution in the vertical wind retrieval based on ECMWF data is introduced. The remaining systematic error of the retrieved vertical wind is estimated to be less than 10 cm/s. A measurement of a flight leg across the Scandinavian mountain ridge is used to characterize gravity waves during strong forcing conditions. The measured vertical wind reaches amplitudes of larger than ± 3 m/s and horizontal wavelengths of 10 km to 20 km. A comparison with WRF-model calculations shows a quite good representation of the horizontal structure of the vertical wind. The amplitude however is obviously underestimated by a factor of 2 and shows maximum wind speeds of ± 1.5 m/s.

Keywords: Coherent Laser Radar, Vertical wind speed, GW-LCYCLE, Deepwave, Airborne Wind Lidar

1. Introduction

Gravity waves (GWs) are well known phenomena in the atmosphere and have a strong impact on vertical transport and exchange of energy and momentum the troposphere and the middle atmosphere [1]. While there is a general understanding of processes launching GWs, the nature of wave source spectra is more complex and less well-understood. Thus, a better characterization of GW sources is an outstanding issue for a proper description of the dynamical coupling of the lower and middle atmosphere.

In order to investigate the entire life cycle of GWs from their excitation towards propagation and dissipation, DLR's Institute of Atmospheric Physics recently initiated/ participated in 3 airborne campaigns namely the GW-LCYCLE I campaign (Kiruna, Sweden, December 2013), the DEEPWAVE campaign (Christchurch, New Zealand, June/July 2014) [2], and the GW-LCYCLE II campaign (Kiruna, Sweden, January/February 2016). In the frame work of these campaigns, combined ground-based and airborne observations were conducted over northern Scandinavia and southern New Zealand, respectively, where both regions in winter-time represent distinguished conditions for the generation of mountain waves which are able to propagate up to the mesosphere.

One key-instrument was DLR's airborne coherent Doppler Wind Lidar (DWL) which was operated from the Flacon F20 research aircraft. In order to carefully characterize mountain waves, both horizontal and vertical wind measurements with high horizontal and vertical resolution and a low statistical uncertainty of several 10 cm/s are desired, where all of these goals can be reached with the DWL. In particular, horizontal and vertical wind is retrieved from line-of-sight (LOS) wind measurements by applying the velocity-azimuth-display (VAD) technique [3] or by steering the beam to Nadir direction leading to a horizontal resolution of about 7 km and 0.2 km, respectively. The vertical resolution for both measurement modes is determined by the laser pulse length and is approximately 100 m.

Vertical wind measurements require an exact nadir-pointing of the laser beam which is challenging to achieve from a moving platform as an aircraft. Thus, small contributions of the horizontal wind component might contaminate the vertical wind measurement. For that reason, a method to correct for slight off-nadir pointing angles by exploiting ECMWF re-analysis wind data and the actual beam pointing direction is developed. After shortly describing the instrument itself in section 2, the vertical wind correction procedure is explained in section 3. In section 4 a few results from a research flight performed on December 13, 2013 during GW-LCYCLE I are discussed.

2. Instrument description

A schematic block diagram of the DWL is shown in Figure 1. The transceiver was developed and built by CLR Photonics (today Lockheed Martin Coherent Technologies) [4-6], the double-wedge scanner system and the data acquisition unit were built at Deutsches Zentrum für Luft und Raumfahrt (German Aerospace Center, DLR).

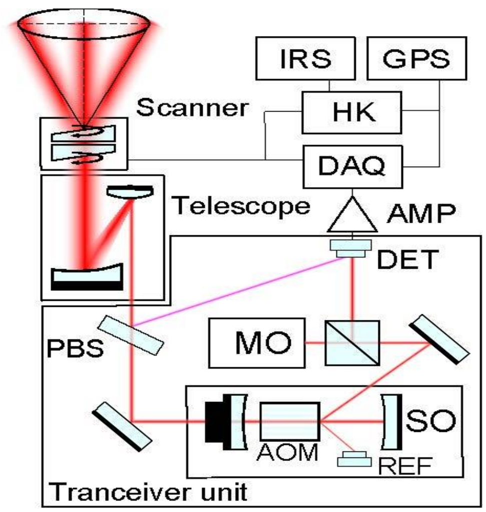

Figure 1. Simplified sketch of the wind lidar system: local oscillator (MO), slave oscillator (SO), acousto-optical modulator (AOM), reference pulse detector (REF), polarizing beam splitter (PBS), signal amplifier (AMP), data acquisition unit (DAQ), housekeeping data acquisition unit (HK), global navigation satellite system receiver (GPS), inertial reference system (IRS).

The transceiver comprises a continuous-wave master oscillator (MO) which is used as an injection seeder for the slave oscillator (SO) and additionally as local oscillator for the heterodyne detection. A part of the MO radiation is coupled into the SO via an acousto-optic modulator (AOM) which is shifting the original MO frequency by about 100 MHz, and thus, permitting determination of the magnitude and sign of the frequency difference between MO and SO which is later needed for wind measurements. The SO produces laser pulses with a wavelength of 2022.54 nm, an energy of 1.5 mJ, a length of 400 ns (~ 120 m) at a pulse repetition rate of 500 Hz. To ensure resonance between the SO cavity length and the MO radiation, the SO cavity length is controlled by the ramp and fire technique [7]. The laser beam is expanded to a diameter of about 10 cm within the telescope after it was passing a polarizing beam splitter (PBS). The expanded laser beam then enters an optical double-wedge scanner which enables to steer the laser beam to any position within a cone angle of 30°. The backscattered light is reflected on the polarizing beam splitter (PBS) and directed to the optical signal detector (DET), where it is mixed with the MO laser. The time-resolved detector signal resulting from each single laser shot is sampled and stored (Fig. 1, DAQ). This procedure leads to a data rate of about 15 Mb/s, and is applied as it gives maximum flexibility for data post-processing.

3. Measurement procedure and data processing

During the GW-LCYCLE I campaign, the DWL was operated in two different acquisition modes, namely in scanning mode or in fixed line-of-sight (LOS) mode, aiming to measure the vertical profile of the three-dimensional wind vector or vertical wind speed, respectively. While operating in scanning mode, a conical step-and-stare scan around the vertical axes with a nadir angle of 20° was performed. 24 LOS wind velocities are measured per one scanner revolution and are used to retrieve the three-dimensional wind vector. During fixed LOS mode operation, the laser beam is intentionally pointed to nadir-direction and thus the measured LOS wind equals the vertical wind speed. In the following, the retrieval of vertical wind speed and potentially needed corrections are discussed. Details about the wind vector retrieval can be found in [8].

In principle, the derived LOS wind speed equals the vertical wind speed, if the laser beam is pointing downwards in nadir direction. Although the lidar system is using an automatic flight attitude correction loop in the meantime (during DEEPWAVE and GW-LCYCLE II) that keeps the set pointing direction, such a control loop was not implemented during the GW-LCYCLE I campaign. Thus, slight off-nadir angles of up to 1° can occur during measurement. As a consequence, the LOS wind speed contains a projection of the horizontal wind speed in LOS direction which has to be corrected. For instance, considering a horizontal wind speed of 30 m/s and an off-nadir angle of 0.5° towards wind blowing direction, the projection in LOS is 0.26 m/s.

Basically, the actual beam pointing direction and the actual horizontal wind speed and direction in a certain altitude have to be known in order to calculate the LOS contribution of the horizontal wind. The beam pointing can be calculated for each measurement by considering the position of both scanner wedges and the lidar installation position which is determined in a separate procedure and which is verified to stay constant during the campaign. The wind vector information can be principally provided by the lidar itself. Though, when the lidar instrument is operating in fixed LOS mode, no information about the wind vector is available. For that reason, usually two or more legs are flown along the same geographical location giving both, the wind vector and LOS wind with a slight temporal discrepancy of about one hour. However, as the coverage of both measurements can be different, not each LOS wind measurement might correspond to a wind vector measurement that can be used for correction. Thus, in order to be able to correct all LOS measurements, ECMWF re-analysis data of wind speed and direction, interpolated to the respective flight track and time, is used. Additionally, the flight leg with the wind vector measurement is used to verify the validity of the ECMWF wind speed data.

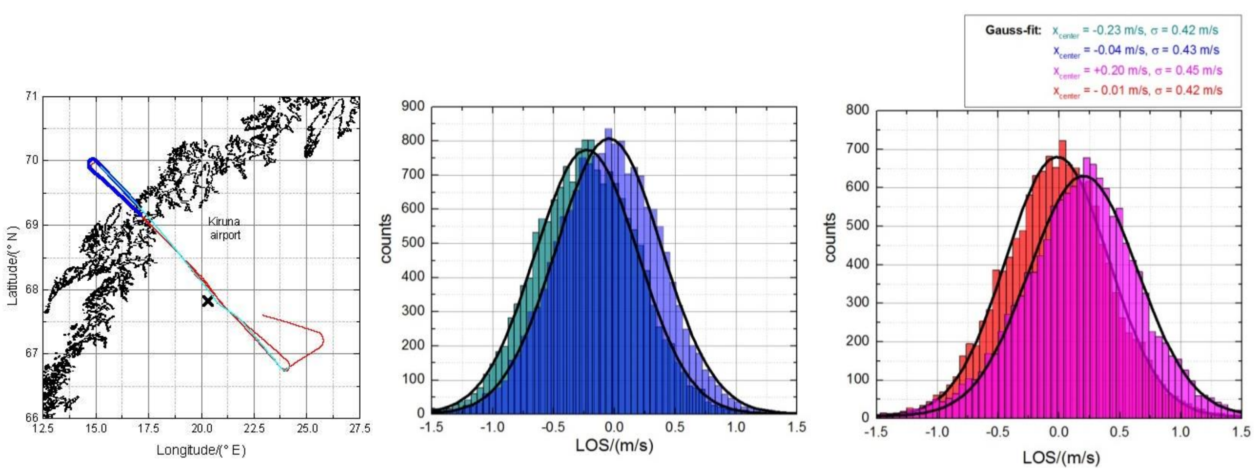

Figure 2. Left: Flight track of a research flight performed on 13. December 2013 (red line). Middle: Histogram of vertical wind speeds derived while flying westwards (left, dark blue line, before curve flight), before correction (green) and afterwards (blue). Right: Same as middle, but flying eastwards (left, dark blue line, after curve flight). Wind speeds before correction are indicated in magenta, the one after correction in red.

In the following, the wind correction procedure is described by means of a research flight performed on December 13, 2013. The corresponding flight track is indicated by the left panel of Fig. 2 (red line). The existence of slight off-nadir pointing gets obvious by plotting the vertical wind speeds measured in westward flying direction (Fig. 2, middle, green) and eastward flying direction (Fig. 2, right, magenta) separately in a histogram. It can be seen that the mean vertical wind speed has an offset of about 20 cm/s with opposite sign for opposite flying directions. This can be explained by a slight off-nadir angle perpendicular to the flying direction and crosswinds from north-west (towards to or away from the laser beam) that leads to a Doppler shift in the measured signal.

Before correcting the vertical wind measurement, the measured horizontal wind speed is used to verify the validity of the ECMWF re-analysis data. The lidar measurement, the ECMWF wind data and the direct comparison of both is shown in Fig. 3. The correlation yields an r^2 of 0.85, and the line fit a slope of 1.00 and an intercept of 0.01 m/s and thus clearly demonstrates the usability of the ECMWF data for correction purpose.

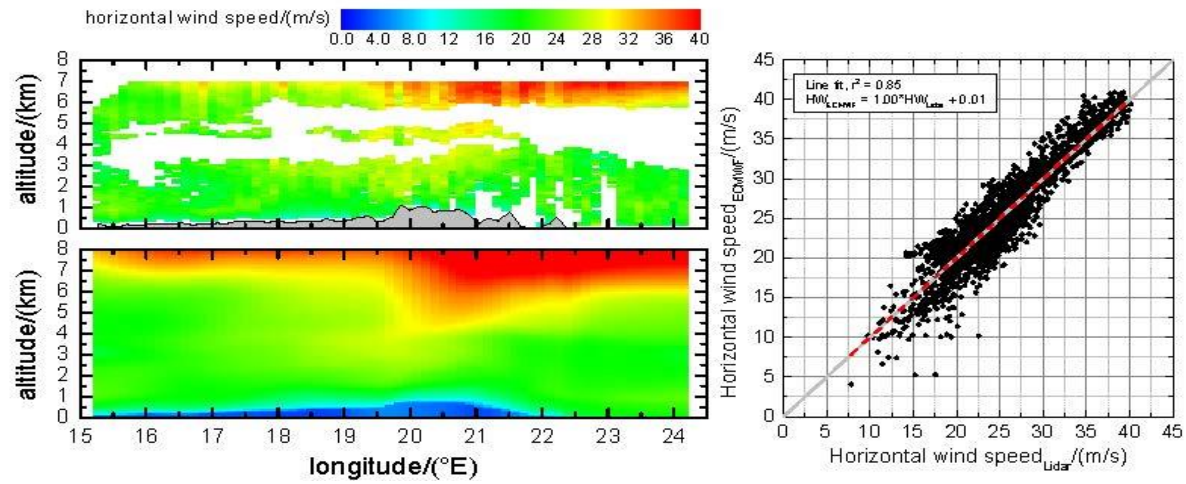

Figure 3. Left, top: Horizontal wind speed derived from lidar measurements (flight leg indicated in Fig. 2, light blue). Left, bottom: Corresponding horizontal wind from ECMWF re-analysis data. Right: Lidar data vs. ECMWF data, line fit (red) and x=y line (gray).

The vertical wind speed histograms after correction are plotted in Fig. 2, middle/blue and right/red, respectively. The mean values are - 0.01 m/s and - 0.04 m/s, which demonstrate the functionality of the correction procedure and give the possibility to estimate the systematic error to be smaller than 0.1 m/s.

4. Results

Corrected vertical wind speeds of a flight leg (13. December 2013) are shown in Fig. 4, top. Furthermore, the in-situ measured vertical wind from the aircraft is indicated at a height of 5.5 km. The data gap in-between is resulting from the pulse length of the laser which prevents to derive wind close to the aircraft. Anyway, the wind speed from the first lidar range gates and the in-situ measured wind speed show the same structure and thus additionally verify the reliability of the lidar data. From the measurement it is obvious that the vertical wind speed is varying around 0 m/s westwards of the Scandinavian mountains (up to 16.8° E). Going further eastwards, the excited gravity waves reach amplitudes of up to 3.5 m/s at the highest elevation at 19.3° E. By analyzing the wind speed in different altitudes (not shown) it can be shown that the amplitudes are decreasing with height. Thus, it is very likely that this particular wave will dissipate in the troposphere and not reach higher altitudes. Furthermore, the horizontal wavelength is determined by wavelet analysis (not shown) to be 10-20 km and thus, represents the orography structure.

A comparison with WRF model calculations (6 km and 2 km resolution, initialized with ECMWF data) as shown in Fig 4, bottom shows quite good accordance with the measurement. The wave-pattern of the vertical wind is well represented. The amplitudes however are by a factor of 2 smaller and reach values of about 1.5 m/s. Explanations for that are under investigation.

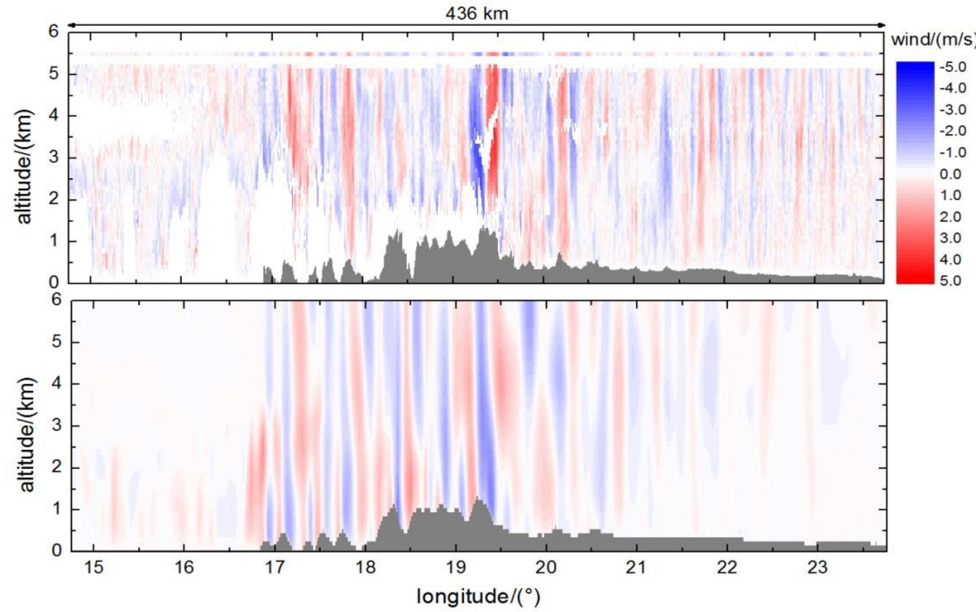

Figure 4. Top: Corrected vertical wind speed derived from lidar measurements performed on a research flight (13. December 2013). Bottom: Corresponding vertical wind speed from WRF-model.

5. Conclusion and Outlook

Recently, DLR's coherent Doppler wind lidar was deployed on three airborne campaigns related to investigate the life cycle of gravity waves. Both, the horizontal and the vertical wind measurements by the lidar are valuable for characterizing tropospheric gravity waves. In the future, in is foreseen to combine the lidar measurements other airborne and ground based instrument data in order to characterize the whole life cycle of gravity waves from excitation to dissipation.

6. References

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