Abstract: This study presents a novel lidar technique to conduct high-spectral-resolution measurements of the atmospheric backscatter. The proposed method, based on a heterodyne detection receiver, allows the separation of the molecular and the aerosol component of the atmospheric backscatter, as well as the analysis of the spectral shape of the Rayleigh–Brillouin line. As in the case of the direct-detection high-spectral-resolution lidars (HSRLs), the separation of the different scattering processes allows an independent system calibration and aerosol extinction measurements. The proposed measurement technique was successfully tested on the DLR airborne Doppler wind lidar system based on data collected during different campaigns and under different atmospheric conditions. In light of these results, further ideas for the implementation of a dedicated heterodyne HSRL (HHSRL) will be discussed.

Keywords: High-spectral-resolution, aerosols, temperature, pressure, heterodyne detection.

1. Introduction

Several types of atmospheric lidars rely on accurate measurements of Rayleigh-Brillouin (RB) scattering for the retrieval of atmospheric parameters like wind, aerosols properties or temperature. These systems, based on the direct detection technique, make use of optical filters to perform spectrally resolved measurements of the atmospheric backscatter.

While heterodyne detection of RB scattering has already been used in some laboratory measurements for the characterization of gases and liquids, e.g., [1], its application to atmospheric measurements was only theoretically discussed [2,3] and limited to the retrieval of atmospheric temperature by relating the measured RB spectrum to RB line shape models.

In this work, measurements conducted by the airborne doppler wind lidar (DWL) of the Deutsches Zentrum für Luft- und Raumfahrt (DLR) during different field campaigns (SALTRACE, DEEPWAVE and A-LIFE) are used to demonstrate the feasibility of a novel lidar measurement technique based on Rayleigh-Brillouin (RB) scattering measurement by a heterodyne detection lidar. The retrieval of high-spectral-resolution measurements of the atmospheric backscatter allows, as in the case of direct detection HSRLs, the separation of the different scattering processes, and thus, an independent system calibration and aerosol extinction measurements.

2. Method

The DLR airborne coherent DWL was built based on an instrument from CLR Photonics, now Lockheed Martin Coherent Technologies, with a scanning and acquisition system developed by DLR that provides airborne wind measurement capabilities [4]. The lidar operates at a wavelength of 2.02254 μm with a pulse full width at half-maximum (FWHM) of 400 ns, a pulse energy of 1–2 mJ, and a repetition frequency of 500 Hz.

The lidar detection is based on a double-sideband receiver with an IF shift of about 100 MHz and a standard bandwidth of 200 MHz. Although first evidence of RB scattering measurements by our system were found with the standard configuration, in order to resolve the complete RB spectrum, which has a half width at half-maximum (HWHM) of about 400 MHz at a 2-μm wavelength, the data acquisition configuration was modified during two flights to conduct high-bandwidth measurements with a sampling frequency of 2 GHz.
Heterodyne lidar signal processing is typically done in the frequency domain. Temporal signals corresponding to each shot are first divided in range gates and the power spectral density (PSD) of each range gate calculated. In order to reduce variability due to speckle and improve the signal-to-noise (SNR), a temporal average of the power spectra corresponding to several shots is calculated. It can be shown [5] that assuming shot noise limit operation, a good approximation of the average measured PSD $P_r$ as a function of range $r$ and frequency $f$ can be written as

$$
(P_r(r,f)) = H(f)[4G^2R^2\eta_h(r)P_{LO}P_a(r,f-f_{IF}) + N_{atm}(r,f) + N_{bkg}(f)]
$$

(1)

where $H$ is the frequency response of the whole receiver chain, $G$ is the receiver chain trans-impedance, $R$ is the receiver photodiode sensitivity $\eta_h$ is the heterodyne efficiency, $P_{LO}$ is the local oscillator (LO) power, $P_a$ is the average PSD of the atmospheric backscatter, $N_{atm}$ is shot noise dominated by the Mie scattering heterodyne current and $N_{bkg}$ is the background noise dominated by the contribution of the LO shot noise ($N_{bkg} = 2qG^2RP_{LO}$, with $q$ the electron charge).

Dividing Eq. 1 by the PSD corresponding to range gates $r_N$ where no atmospheric return was received (range larger than aircraft altitude), a normalized dimensionless PSD can be written as

$$
R(r,f) = \frac{P_r(r,f)}{P_a(r_N,f)} - 1 = \frac{2B\eta_h(r)P_a(r,f-f_{IF})}{q} + \frac{N_{atm}(r,f-f_{IF})}{2qG^2RP_{LO}}
$$

(2)

where the first term is proportional to the atmospheric backscatter (Mie and RB) and the second term is proportional to the noise induced by the first term. Due to the different nature of the Mie and RB scattering process, the Mie scattering corresponds to a narrow-band signal (about 1 MHz) while the RB scattering corresponds to a broad band signal (about 400 MHz HWHM). Based on this difference, the contribution of the RB scattering $P_{Ray}$ can be obtained by integrating Eq. 2 over a broadband window (BB) centered around IF where the Mie scattering contribution is zero (lidar is vertical pointing and no deviation from IF is expected from wind contribution). In a similar way, the contribution of the Mie scattering can be obtained by integrating over a narrow-band window (NB).

$$
P_{BB}(r) = \sum_{f \in BB} R(r,f) \approx k_{det}(r)k_fP_{Ray}(r) + k_nN_{atm}(r)
$$

(3)

$$
P_{NB}(r) = \sum_{f \in NB} R(r,f) \approx k_{det}(r)P_{Mie}(r)
$$

(4)

where $k_{det}(r) = 2B\eta_h(r)/qB$ and $k_n = 1/(2qG^2RP_{LO}B)$, with B the detection bandwidth. Since depending on the detection bandwidth not all the RB scattering bandwidth is covered, a correction factor $k_f$ is included to take this into account. In the case of the Mie scattering, and since the integration bandwidth is small, the contribution of the Mie induced noise can be neglected.

Finally, based on the lidar equation, $P_{ub}$ and $P_{pb}$ can be written as a function of the atmospheric molecular and aerosol backscatter

$$
P_{BB}(r) \approx k_{Cal}(r)k_f\beta_m(r)T^2 + k_nN_{atm}(r)
$$

(5)

$$
P_{NB}(r) \approx k_{Cal}(r)\beta_a(r)T^2
$$

(6)

where $k_{Cal}(r) = k_{det}(r)P_k(r)/A$, with $P_k$ equal to the transmitted power and $A$ the receiver area, $\beta_m$ is the molecular backscatter coefficient, $\beta_a$ the aerosol backscatter coefficient and $T$ the atmospheric transmission.

3. Results

Figure 1 presents an example of measurements performed with the high bandwidth configuration, under low aerosol load conditions, during the A-LIFE campaign. Although the flight altitude was 9.9 km for this case study, due to limitations of the acquisition system, only measurements down to 5.9 km were recorded.

The normalized PSD $R(r,f)$ presented in Fig. 1(a) was calculated from a FFT of 2048 samples, equivalent to range gates of about 150 m and an averaging time of 210 s. For the background noise correction process, the average of the spectra corresponding to range gates from 20 ($r > 3.5$ km) and onwards were used after replacing the samples between 95 and 115 MHz, containing the Mie spectrum, by a linear interpolation.
Figure 1(b) show the RB scattered power as a function of range resulting from integrating the received power for each range gate and the NB channel (indicated by green lines in Fig. 1(a)), after correction by Mie signal induced noise ($k_nN_{atm}$).

![Figure 1(a)](image1.png)  
![Figure 1(b)](image2.png)  
![Figure 1(c)](image3.png)  
![Figure 1(d)](image4.png)

Figure 1. Analysis on data acquired during the A-LIFE campaign using the high-bandwidth receiver configuration.

The analysis presented in Fig. 1(d) show the PSD for a range gate 900 m below the aircraft together with the expected RB spectral shape derived from the Tenti S6 model and considering the spectral folding effect due to the small IF. The agreement between the measurements and the model provide further evidence about the RB origin of the broadband signal observer by the lidar.

In order to provide further evidence about the molecular origin of the observed broadband signals, an analysis of the change in the received power from a range gate at a fixed distance from the aircraft during descending or ascending flight sections was conducted. In this way, no characterization of the heterodyne efficiency is required, and the range gate with the maximum SNR can be selected. Furthermore, and since a range gate close to the aircraft can be chosen, the effects of the unknown atmospheric extinction can be minimized. In this way, the Rayleigh backscatter power is proportional to the molecular backscatter coefficient corresponding to the range gate altitude.

Figure 2 presents the results derived from Eqs. 5 and 6 based on measurements carried out during the SALTRACE campaign. By fitting the vertical profile of $P_{BB}$ (after correction by Mie induced noise) obtained with the previously described techniques to a vertical molecular backscatter profile calculated based on in-situ temperature and pressure measurements, $k_{Cal}$ was calculated (Fig. 2(a)). This calibration constant was then applied to retrieve a vertical aerosol backscatter profile (Fig. 2(b)). In order to perform a validation of the results, the retrieved profile was compared with an aerosol backscatter profile derived by the ground-based aerosol lidar POLIS. Since the DWL operates at 2 um and detects only one polarization component, a wavelength conversion coefficient and depolarization extinction correction was applied. The results show a good agreement between both retrievals.
Figure 2. Retrieved vertical profiles of molecular and aerosol backscatter profiles during SALTRACE.

4. Conclusions

To our knowledge, first-time measurements of RB scattering by an heterodyne detection lidar are presented in this work. Additionally, a novel calibration technique that doesn’t require of additional information from aerosol ground-based lidars [6] was briefly described. Despite a series of instrumental limitations mainly related to the original purpose for which the instrument used in this study was developed (e.g. limited wavelength and power, measurement of only one polarization component), the bases for a novel detection architecture for the retrieval of temperature and aerosol optical properties were settled. This proof of concept for a HHSRL shows the potential and requirements of a system based on this technique and guides the future implementation of a system with a large range of applications, including temperature, wind, and aerosol measurements.

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5. References