Coherent Doppler lidar for aerosol-cloud-dynamics interaction studies operating at 532.25 nm with a 3.2 GHz data acquisition

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Abstract: A coherent Doppler lidar (CDL) operating at 532.25 nm wavelength with a 3.2 GHz data acquisition is developed. The technical setup is described. One atmospheric measurement case is analysed to point out the instrument's ability to observe cloud, precipitation, and aerosol particles of very different sizes in one Doppler spectrum. A second case highlights the coherent detection of the broadband Rayleigh-Brillouin (RB) spectrum and the possibility for a Mie signal calibration. The system's benefits compared to 1.55 µm CDLs are discussed. The system's capabilities were found to be promising for enhancing the knowledge about aerosol-cloud interactions.

1. Introduction

Aerosol-cloud-dynamics interactions usually take place within the turbulent environment in and around clouds. This entanglement complicates any attempt to estimate the role of the individual processes. One approach is to utilise Doppler techniques to achieve a separation of the involved particle species. So far, multiple instrument approaches have been used for covering the manifold sizes and fall velocities of the atmospheric targets [1,2]. In the scope of the ACTRIS-D project (German contribution to the European Aerosol, Clouds and Trace Gases Research Infrastructure), the coherent Doppler lidar ProDoLi operating at 532.25 nm wavelength and with a 3.2 GHz broadband data acquisition is being developed. The high backscatter signal level, Doppler resolution, and the ability to detect the molecular backscatter signal enables observations of aerosol particles, hydrometeors and clear air at the same time and at higher temporal, spatial, and velocity resolution compared to existing IR systems.

This paper presents the technical setup and properties and highlights the capability for simultaneous multiple peak and RB signal detection in one Doppler spectrum. The opportunities provided by the unique system are discussed and future improvements and application fields are derived.

2. Technical setup and properties

ProDoLi is a unique combination of a lidar transmitter operating at λ_0= 532.25 nm wavelength (LiTra HSR, Abacus Laser GmbH) and a $B_{\mathrm{DAQ,max}}$ = 3.2 GHz data acquisition (Waverider, Licel GmbH). The principle of the system is shown in Fig. 1.

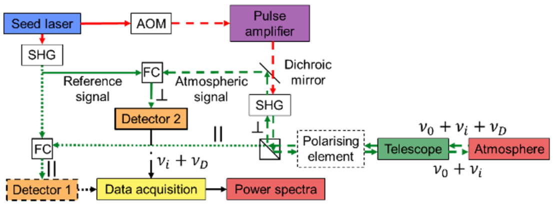

Figure 1. Principal setup of CDL ProDoLi. AOM – acusto-optic modulator, SHG – second harmonic generator, FC – 2x2 fibre coupler, solid line – continuous laser beam, dashed line – pulsed laser, dot-dashed line – beat signal, dotted line – not implemented, red – 1064.5 nm, green – 532.25 nm, black – electronical signal, || - parallel polarised light, ⊥ - perpendicular polarised light, polarisation plane with respect to the optical table.

Table 1 summarises the technical properties of the system. A paper detailing the optical and electronical setup will be published after several technical improvements (see Discussion) have been done.

Table 1. Properties of CDL ProDoLi.

Technical parameter	Unit	Value
Emitted wavelength λ_0	nm	532.25
Intermediate frequency ν_i	MHz	80
Pulse duration τ	ns	680
Pulse repetition frequency f_{PR}	kHz	2
Maximum detection bandwidth (Waverider) $B_{DAQ,max}$	GHz	3.2
Current detection bandwidth B_{DAQ}	GHz	1.6
Current detector bandwidth B_{Det}	GHz	1.4
Height resolution ΔR	m	96
Frequency resolution Δf	MHz	1.5625
Velocity resolution $\frac{d\nu_D}{dv}$	MHz/ (m/s)	3.76

The seed laser is a tunable, narrow-linewidth laser emitting a continuous wave at 1064.5 nm. The AOM forms pulses of τ = 680 ns pulse length with a pulse repetition frequency of f_{PR} = 2 kHz. The intermediate frequency ν_i is currently 80 MHz. The pulse power is increased by a four-stage amplifier unit consisting of two fibre amplifiers, one large-mode-area amplifier and one crystal amplifier. The frequency of the infrared pulses is doubled by an LBO crystal after passing a dichroic mirror. The green pulses are transmitted through a Galilei telescope expanding the beam to approximately 44 mm in diameter. Within the atmosphere, a Doppler shift of $\frac{d\nu_D}{dv}$ = 3.76 MHz per m/s is introduced by the moving particles, which is by a factor of 3 higher compared to CDL at 1.5 µm.

The backscattered atmospheric light is received by the same telescope. A polarisation beam splitter separates the perpendicular and parallel polarised light, whereas only the former is analysed at the moment. The perpendicular polarised light passes the LBO crystal again and is separated from the IR pulses by the dichroic mirror. The atmospheric signal is then coupled into one port of a 90/10 fibre coupler by an aspheric collimator lens with a short focal length. In the fibre coupler, the superposition of the atmospheric and the reference signal yields an optical beat signal, which is recorded by a B_{Det} = 1.4 GHz biased detector (Detector 2). The spectral analysis is done by the data acquisition, which is currently limited to B_{DAQ} = 1.6 GHz (sampling rate of 3.2 GS/s). The length of the discrete Fourier transform (DFT) is 2048, which corresponds to a range gate length of 640 ns and a height resolution ΔR of 96 m. The spectral width of the rectangular, τ = 680 ns long pulse is about 1.3 MHz and smaller than the frequency resolution of the DFT of Δf = 1.5625 MHz. Hence, the spectral resolution is limited by the frequency resolution of the DFT.

Detection channel 1 is intended to detect the parallel polarised light, which yields further information about the shape of the atmospheric particles. The polarising element can then be inserted to switch the detectors for parallel and perpendicular polarised light, which makes a detector calibration possible.

3. Detection of multiple particle species in one Doppler spectrum

For system evaluation, ProDoLi was set up in a laboratory within 100 m of a Halo Streamline Doppler lidar, an RPG 94 GHz cloud radar [3], and a PollyXT multiwavelength Raman polarisation lidar [4]. A data processing routine yields overview plots, e.g., Fig. 2. The basis are 1.6 GHz wide Fourier spectra centred at the intermediate frequency ν_i, which is introduced to determine the direction of motion. Narrowband peaks within a range of ±40 MHz (±10 m/s) around ν_i are attributed to particle scatterers. Panel a displays the intensity of the strongest aerosol or cloud particle backscatter. The corresponding particle velocity is shown in panel b. The broadband RB signal (panel c) is measured simultaneously within the complete 1.6 GHz spectrum and is analysed in the spectral range of 312 - 1400 MHz. Hence, the RB signal is spectrally separated from the Mie signal. Panel d reveals the number of peaks determined in the Doppler spectra.

An atmospheric measurement performed at Leipzig on 8 August 2023 is shown in Fig. 2. There are several precipitation events with multiple detected peaks in the spectra (panel d). The Doppler spectrum measured at 1152 m height at 08:28:01 UTC (marked by the black lines in Fig. 2) is compared with the nearest one in time and space of the RPG cloud radar in Fig. 3. The positions (velocities) of three peaks match well. These peaks can be attributed to larger precipitation particles (ice crystals, water drops), because the radar is sensitive only to these particles.

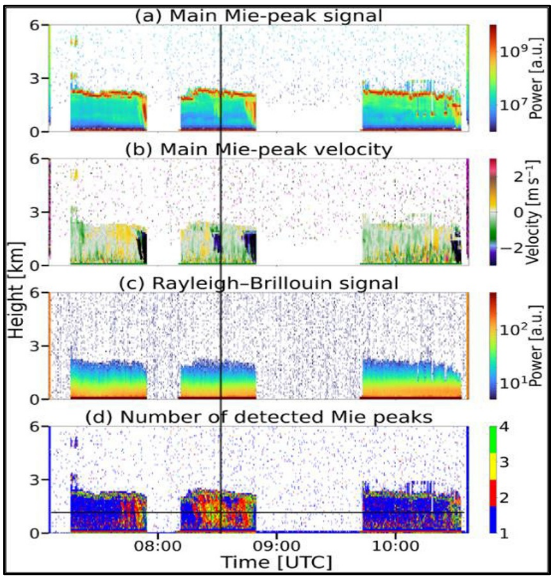

Figure 2. Atmospheric measurement at Leipzig, Germany on 8 August 2023 between 07:05:00 and 10:37:00 UTC. Integration time is 10s. The case is characterised by several precipitation events with multiple peaks in the spectra (panel d) and a liquid cloud layer around 2-2.5 km. The black lines mark the location that is analysed in Fig. 3.

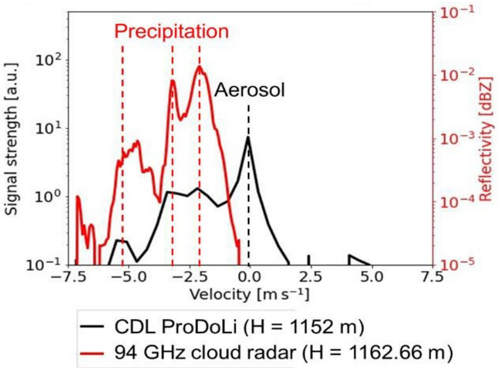

Figure 3. Comparison between ProDoLi (signal strength, left axis) and 94 GHz cloud radar (RPG, reflectivity, right axis) Doppler spectra. In addition to the precipitation particles, ProDoLi detects the aerosol peak. Timestamp: 8 August 2023, 08:28:01 UTC.

ProDoLi can distinguish these precipitation particles as well and shows a fourth peak in addition. This peak is attributed to aerosol particles, because the PollyXT and Doppler lidars prove the presence of aerosol before and after the precipitation. Hence, ProDoLi is sensitive to cloud/precipitation and aerosol particles of very different size in a single measurement, due to the larger spectral peak separation at different velocities compared to conventional IR CDLs.

4. Detection of the Rayleigh-Brillouin spectrum

A second measurement performed at Leipzig on 6 July 2023 is shown in Fig. 4.

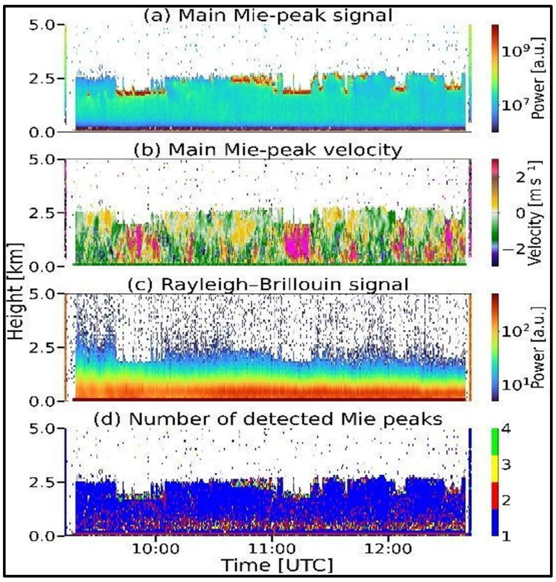

Figure 4. Atmospheric measurement at Leipzig, Germany on 6 July 2023 between 09:13:01 and 12:42:52 UTC. Integration time is 10s. The case is characterised by broken cloud fields between 1.75 km and 2.5 km and a turbulent boundary layer below. The Mie and RB signal profiles at 11:19:20 UTC are depicted in Fig. 5.

The RB signal (panel c) reaches up to 2.5 km and is occasionally limited by clouds at around 2 km height, e.g., between 11:05 and 11:20 UTC. The observation of the molecular backscatter signal (signal strength P_{mol}, red line in Fig. 5) with a CDL is an achievement of the project and allows the calibration of the Mie signal (signal strength P_{aer}, black line Fig. 5) according to Eqn. 1. The ratio (green line in Fig. 5)

$$\frac{P_{\mathrm{aer}}}{P_{\mathrm{mol}}} = K_{\mathrm{lidar}} \frac{\beta_{\mathrm{aer}}}{\beta_{\mathrm{mol}}} \quad (1)$$

allows the determination of the aerosol backscatter coefficient β_{aer} from the ratio of the signal strengths, the lidar constant K_{lidar} and the (calculated) molecular backscatter coefficient β_{mol}.

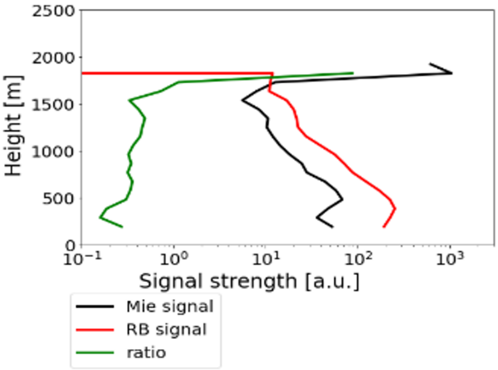

Figure 5. Exemplary Mie (black) and RB (red) profiles at Leipzig, Germany on 6 July 2023 11:19:20 UTC. The green line is the ratio of the signal strengths.

5. Discussion

To our knowledge, it could be demonstrated for the first time, that a CDL operated in the visible wavelength range can perform atmospheric measurements. Switching to 532.25 nm brings several advantages compared to conventional CDLs operating at 1.55 µm wavelength. The Doppler shift per velocity $\frac{d\nu_D}{dv}$ depends on λ^{-1}. A decrease of the wavelength by a factor of about 3 compared to commercially available systems increases the spectral distance between particles of different speed, and allows the detection of multiple peaks in the spectra while maintaining the same range resolution. Another advantage is the stronger molecular backscatter ($\propto \lambda^{-4}$) by a factor of about 81 (19 dB) compared to CDLs operating in the infrared wavelength range. The second innovation is the broadband data acquisition (B_{DAQ}= 1.6 GHz) which enables the observation of a greater part of the broadband RB spectrum from the molecules.

The CDL fills an instrumental gap between current Doppler lidars and radars due to its sensitivity to multiple scatterers of different sizes, e.g., cloud particles, precipitation, and aerosol particles, and their velocities at the same time. The detection of the backscatter signal from the molecules allows the calibration of the Mie signal, which enables the determination of the particle backscatter coefficient β_{aer} by the high-spectral resolution lidar method. In synergy with other radar and lidar techniques, ProDoLi shall be applied to study ice formation processes in mixed-phase clouds. The discrimination of particles of different sizes can yield a particle size spectrum. A spectral analysis of the broadband RB signal could enable the observation of clear-air turbulence as well.

Future technical improvements address the following components: The optical losses have to be reduced. The biased detector will be replaced by a 1.6 GHz balanced detector to suppress the seed laser's intensity noise. The implementation of the second detection channel for polarisation discrimination will provide information about the particle shape. A switch to 1.04 GHz intermediate frequency would shift the combined Mie-RB spectrum within the 1.6 GHz bandwidth, which enables the observation of both slopes of the RB spectrum. At the moment, only the right part is visible, whereas the left part is folded in.

6. Acknowledgement

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7. References

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