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Wind Measurements up to 25km based on Aerosol Backscatter with a Novel, Multi Field of View Lidar

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Abstract: We present the first set of simultaneous horizontal and vertical wind measurements obtained from aerosol backscatter, covering altitudes between 3 and 25 km. These measurements were made possible by using the novel VAHCOLI lidar system of the Leibniz Institute of Atmospheric Physics in Germany. Designed as a multi-purpose system incorporating Doppler-Mie, Doppler-Rayleigh, and Doppler-resonance lidar techniques for studying the middle atmosphere, the system has been upgraded to probe wind dynamics across five fields of view. Comparisons with winds from ECMWF (European Centre for Medium-Range Weather Forecasts) and Aeolus satellite data show good agreement for horizontal wind components but reveal a significant underestimation of vertical winds by ECMWF. By leveraging measurements across multiple fields of view, we highlight the system's capability to detect small-scale wind asymmetries, underscoring its value for atmospheric research.

1. Introduction

VAHCOLI (Vertical and Horizontal COverage by LIdar) introduces a novel concept for a network of compact, yet highly capable, general-purpose lidar systems [1]. With this network we aim to provide continuous (24/7) measurements of temperatures, winds, and aerosols in the middle atmosphere (approximately 3-110 km) with high temporal and vertical resolution. By combining multiple lidar units into a network, it is possible to achieve four-dimensional coverage, capturing different horizontal scales ranging from a few hundred meters to several hundred kilometers, depending on the spatial arrangement of the individual units.

The VAHCOLI units use a novel diode-pumped alexandrite ring laser as an emitter, specifically tuned to the potassium-D1 line (770 nm) [2,3]. This enables the lidar to perform Doppler-Mie, Doppler-Rayleigh, and Doppler-resonance measurements simultaneously using identical technology, thanks to an innovative laser and novel spectroscopy method. This method marries the alexandrite laser's excellent spectral characteristics with ultra-narrowband filters, which are stabilized to sub-megahertz precision. The narrowband filtering technique not only allows for the simultaneous capture of Mie, Rayleigh, and resonance signal components but also significantly reduces solar background, facilitating operations during daylight. Furthermore, the entire system is housed within a single enclosure, custom made in house. This integration leads to lidar units with a volume of only one cubic meter and a weight below 500 kg for the purely vertical configuration.

2. Multi Field of View Capabilities

In alignment with the objectives of VAHCOLI, we have developed and implemented a Multi Field of View (MFOV) upgrade for the VAHCOLI lidar system. This enhancement is designed to improve our atmospheric observation capabilities across a broad spectrum of horizontal and vertical scales. The upgrade features four lens telescopes tailored towards lidar needs, each tilted at 30 degrees from zenith in the cardinal directions: north, south, east, and west. To facilitate rapid switching between different fields of view for both the power laser and detection bench, a two-axis galvanometer scanner is employed.

A CAD drawing illustrating the updated system is presented in Figure 1. The L-shaped MFOV upgrade is affixed to the core unit of the lidar, substantially augmenting its observational prowess without notably increasing the instrument's size. The two-axis galvanometer scanner has been seamlessly integrated into the core unit. With the upgrade, the total weight of the instrument is approximately 500 kg, and the edge length of the instrument has been modestly extended by 30 cm, resulting in an overall length of approximately 130 cm. We note, that additionally to switching between the five telescopes to generate five fields of view with large separation, the flexibility of the galvanometer scanner also allows us to generate multiple fields of view within a single telescope, to observe small scale processes.

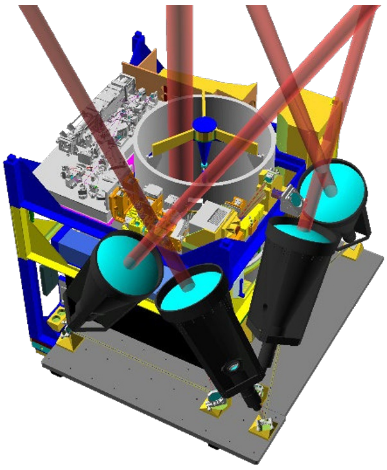

Figure 1. CAD drawing of the multi field of view upgrade mounted to the core unit.

3. Mie-Wind method

The VACOLI instruments employ a spectral measurement technique that involves rapidly and precisely scanning the frequency of the Alexandrite power laser across the highly stabilized filters, facilitating the measurement of backscattered spectra. The scan range and pattern is set within the instruments control software for different scientific goals. Figure 2 depicts a typical spectrum obtained using the Mie-channel of the instrument between altitudes of 9.5 and 10.5 km, with an integration time of 20 minutes and a scan range aimed toward aerosol observations. Within this spectrum, the narrowband Mie-peak is distinctly visible atop the Rayleigh background. The line of sight wind, inferred from the Doppler-shift of the Mie-peak, is determined by fitting a Voigt function to the peak, as elaborated in [4]. This fitting process is selected due to the convolution of the spectral shapes of the filter (approximately Airy), the laser (approximately Voigt), and the broadening effects caused by wind fluctuations (assumed to be Gaussian).

As illustrated in Figure 2, the Rayleigh backscatter forms an almost linear background in the spectrum measured in the Mie-channel, since it is spectrally much broader. Thanks to the narrow bandwidths of both the laser (Full Width at Half Maximum, FWHM, ~3.3 MHz) and the filter (FWHM ~7.5 MHz), Rayleigh scattering is suppressed in this channel by a factor of approximately two orders of magnitude. This significant suppression enhances the sensitivity to aerosols, enabling ground-based wind measurements based solely on aerosol backscatter up to typical altitudes of 25 km. Beyond this altitude, aerosol backscatter—and consequently, the signal in the Mie-channel—dramatically decreases.

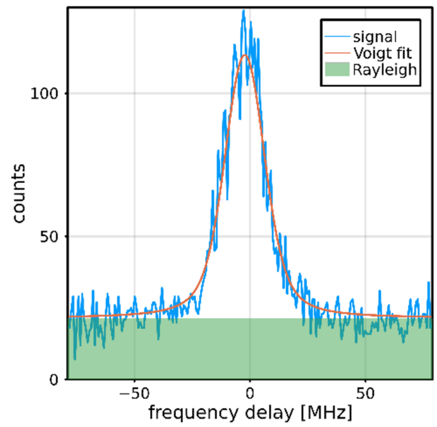

Figure 2. Typical spectrum as measured with the Mie-Channel of the VAHCOLI 1. The background consists of Rayleigh scattering.

4. Mie-Winds up to 25km

The first field tests of a VAHCOLI instrument, enhanced to include five fields of view, were conducted in late 2022. From noon on December 16th to December 18th, the system operated continuously for over 48, as detailed in [4]. Winds derived from these measurements spanned an altitude range from 3 to 25 km, as demonstrated by the vertical winds illustrated in Figure 3. The average measurement error for vertical wind between 3 and 20 km was 0.15 m/s, while the observed vertical wind fluctuations were approximately 1 m/s in amplitude.

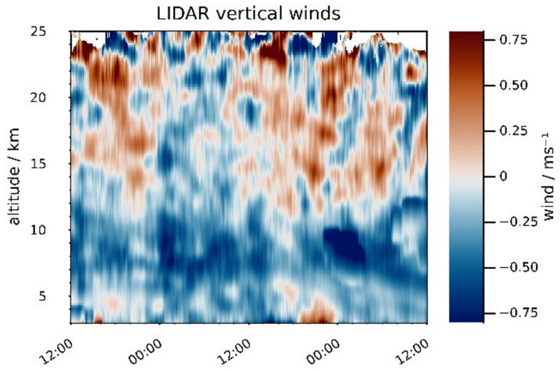

Figure 3.Vertical winds measured with the VAHCOLI 1 instrument between noon on the 16th and 18th December 2022. An integration window of 120 minutes and 1km, shifted in 2 min and 200 m steps is used.

Horizontal winds, observed during the same measurement period, are depicted in Figure 4. Notably, a reversal of meridional wind at the tropopause altitude is clearly evident. Throughout the measurement period, some icing occurred on the lens telescopes, leading to a diminished signal in the zonal fields of view and, consequently, gaps in the wind data retrieval. As consequence, an automatic telescope heater was integrated.

5. Comparison with ECMWF and Aeolus

To benchmark our findings, we compared our data against outputs from the ECMWF integrated forecast system and observations from the Aeolus satellite. As depicted in Figure 4, there is a qualitative alignment between the ECMWF horizontal winds and our measured horizontal winds, with the system successfully capturing the most significant wind patterns. However, a detailed analysis uncovers some minor discrepancies between our measurements and the ECMWF winds.

When comparing our measured vertical winds with those predicted by ECMWF (for more details see [4]), we observed a significant underestimation by ECMWF—roughly an order of magnitude lower than our findings.

Given that the VAHCOLI instrument spans most of the Aeolus satellite's altitude range and provides precise three-dimensional Mie-winds, we seized the opportunity to compare our data with that of the only spaceborne Doppler-wind lidar during an overflight on December 16, 2022. The outcomes of this comparison, illustrated in Figure 5, reveal a minimal bias between the VAHCOLI instrument and Aeolus, less than 0.12 m/s, and a random error of 3.31

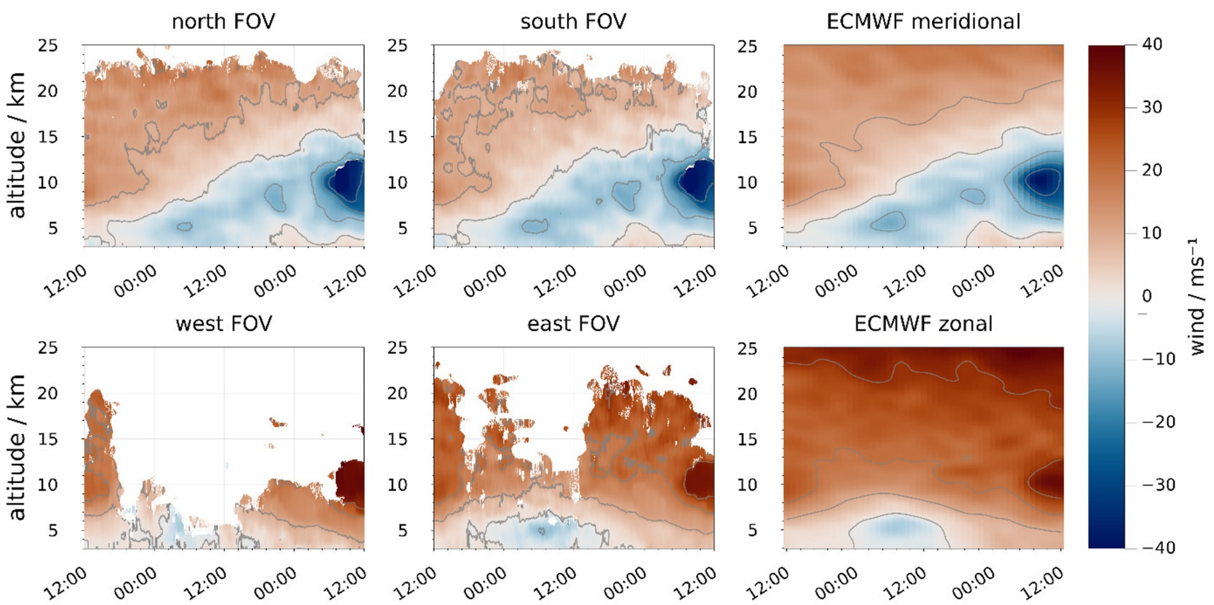

Figure 4. Horizontal winds measured along the four tilted fields of view between December 16th 2022 12:00UT and December 18th 12:00UT together with the meridional and zonal ECMWF winds. Data gaps in the west and east FOV are due to icing problems.

m/s. These results position the developing VAHCOLI network as a promising tool for validating of future space-born lidars.

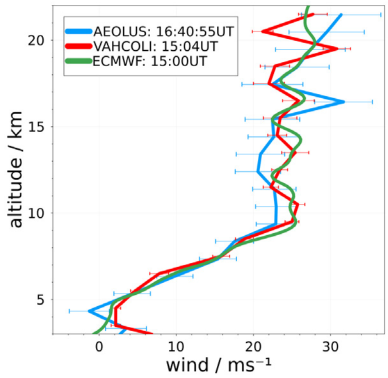

Figure 5. VAHCOLI winds measured on the 16th December 2022 (red) together with the Aeolus winds (blue) and ECMWF winds (green), also projected to the Aeolus. VAHCOLI and ECMWF three-dimensional winds are combined and projected to the horizontal line of sight (HLOS) vector of Aeolus.

6. Comparison of individual FOV

The integration of five fields of view within the VAHCOLI system facilitates a direct comparison of meridional winds measured along two distinct FOVs. The design, which includes a 30° tilt off-zenith, causes the distance between individual FOVs to expand with altitude. This unique configuration enables the observation of small-scale wind asymmetries using a single instrument over scales of a few km. For observing large-scale phenomena, a network of lidars becomes necessary. Conversely, smaller scales of less than 100 meters can be effectively studied using multiple FOVs within a single telescope. The technology required for this level of observation is already incorporated into the system.

7. Conclusion and Outlook

We present wind measurements from a VAHCOLI instrument, which has been enhanced to observe atmospheric dynamics across five fields of view. Leveraging narrowband aerosol backscatter, the system delivers high-quality, three-dimensional wind measurements up to an altitude of 25 km. Our comparisons with ECMWF and Aeolus data indicate a generally good agreement, particularly for horizontal wind components. However, we identified a significant underestimation by ECMWF in the vertical wind measurements, by an order of magnitude. The innovative setup with five fields of view not only facilitates the measurement of 3D winds but also allows for the exploration of wind dynamics across the transition from microscale to mesoscale (1,000 to 10,000 meters), a capability afforded by the spatial arrangement of the individual fields of view.

The results shared herein were obtained using a preliminary optical setup. With the deployment of the final optical arrangement in a new version of the instrument, we anticipate a marked improvement in system performance, which in turn will allow us to use multiple FOVs within a single telescope.

The methodologies developed for the multi-field of view configuration will be instrumental in two forthcoming projects, EULIAA & LidarCUBE, which aim to expand network coverage, facilitate industry transfer and further develop the systems. The promising comparison between VAHCOLI and Aeolus winds underscores our conviction that a network of such instruments would significantly enhance validation efforts for the successors of the Aeolus satellite.

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