

A SPECTROSCOPIC DOPPLER LIDAR FOR A FUTURE SPACE MISSION

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ABSTRACT

The Leibniz Institute of Atmospheric Physics and the Fraunhofer Institute for Laser Technology have developed a compact, 1 m³ ground-based Doppler lidar system capable of unattended, 24/7 middle-atmosphere profiling between 2 and 120 km. By combining a frequency-scanning, narrowband Alexandrite ring laser with advanced post-processing, the instrument achieves MHz spectral resolution for simultaneous 3D wind and aerosol measurements. Within the ongoing EULIAA-project, we develop three advanced Doppler lidars focusing on the lower 50 km altitude. All three systems achieve continuous unattended and autonomous operation at different validation sites. We installed the first system operating at the potassium resonance line (770 nm) at ALOMAR in Norway, 69° N. This lidar has been in unattended operation for 10 months. The second system at the iron resonance line (386 nm) was tested at OHP in France, 44° N for 10 weeks and is currently transferred to Payerne, Switzerland. We built the third system for helicopter transport and installed the lidar on top of the Sphinx station of HFSJG, 47° N in Switzerland at 3580 m height. All three system achieve continuous operation with very little maintenance work and immediately after reaching their destinations.

Keywords: Doppler lidar, spaceborne, lidar, spectroscopy, wind, turbulence, troposphere, stratosphere, mesosphere

1. INTRODUCTION

A compact, ground-based Doppler lidar developed by Leibniz IAP and Fraunhofer ILT provides day- and nighttime wind, temperature, aerosol, turbulence, metal observations including polarization/depolarization measurements for aerosol characterization in the altitude range between 2 and 120 km altitude [1]. A single instrument combines a diode-pumped, single-frequency Alexandrite ring laser operated in a deep Fraunhofer line with a matched, ultra-narrowband high-finesse receiver. A scanner sequentially addresses one vertical field of view (FOV) and two FOVs tilted 30° off zenith in orthogonal directions, enabling 3D retrievals with a single transmitter/receiver in a <1 m³ enclosure suitable for unattended operation [2].

The time-resolved spectroscopic approach combines a pulsed laser with long pulse (1.1 μs) with advanced mathematic post processing to circumnavigate the Fourier-Transform limit. A classical spectral analysis serves as reference for the development of this novel method. Both spectroscopic approaches allow Doppler-Mie wind measurements from the troposphere to the stratosphere under all circumstances from a few photons only [2]. We achieve less than 1 m/s uncertainties up to 20 km altitude within 16 sec integration and 150 m altitude resolution. We measure at the same time aerosols at any altitude with high resolution. During clearest sky conditions and depending on the integration time, aerosols are visible without gaps from 2 km to roughly 30 km depending on the upper edge of the aerosol load. Because of the high time/altitude resolution, we can also measure turbulence in the troposphere and lower stratosphere from the power spectral density. A direct measurement of the spectral broadening caused by wind shears and turbulence becomes possible with the advantage of being able to obtain turbulence with a single measurement. Whereas the data analysis for Doppler broadening and turbulence is still under development and not shown here wind/aerosols/depolarization/temperature are analyzed already within the lidar in real-time.

Within the EULIAA project (www.euliao.eu) the next generation lidars as successor of VAHCOLI [3] are validated against established system at various sites. An important part of the project is the demonstration of autonomous unattended operation as a network with real-time analysis. The major goal is closing observation gaps for weather services or climate research. Whereas the EULIAA-project is focusing on the lower 50 km, we originally developed the general-purpose spectroscopic approach decades ago for the mesosphere. Based on a flash lamp pumped Alexandrite ring laser we observed Doppler temperature measurements, metals and aerosols (NLC) in the mesosphere for more than 2 decades worldwide

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within a containerized system [4]. Based on the same spectroscopic approach EULIAA is not limited to the lower atmosphere and additionally observes the metal layers and NLC in the mesosphere already. The developed technology is suitable for an airborne lidar or space mission and the current dimensions (1 m^3), weight ($<400\text{ kg}$) and power consumption (500 W without cooling) of the ground-based lidar unit already come close to the required specifications.

2. NEXT GENERATION LIDARS: EULIAA



Figure 1. Left panel: EULIAA-IR1 at Kühlungsborn, Germany during early test measurements. The lower part contains the chiller in a separate housing. The upper part of $1\times1\text{ m}^3$ contains all hardware of the lidar in a sealed and temperature stabilized 3D-printed housing. Right panel: EULIAA-UV2 on top of the Sphinx station at HFSJG at 3580 m altitude.

For EULIAA we build three lidars and test them now throughout Europe. A first field campaign for validation of the first lidar EULIAA-IR1 began in July 2025 at IAP, 54° N (Baltic Sea, Germany) and continued in October at Andøya, Norway, 69° N with autonomous maintenance free measurement over more than 10 months at the potassium Fraunhofer line (770 nm). Similar to the former VAHCOLI, the sealed housing is 3D-printed at the IAP as well as the telescope and the receiver. EULIAA-IR1 during an early test is shown in Figure 1, left panel. We built the lidar largely from off-the-shelf components whenever possible to keep the overall cost low. Within the project, we transfer missing optical components such as telescope optics into the industry for standardized future systems. The receiver is based on a patented optical system, allowing a compact optical setup in a lightproof structure. The optical setup with three telescopes, seeder, pulsed laser and receiver with two interferometers fits onto a breadboard of $80\times80\text{ cm}^2$. The lower compartment contains all electronics, UPS and firewall. The lidar itself including all additional subsystems like weather station, ADSB-receiver, IR-camera for air safety, hatch or dehumidifier requires $\sim500\text{ W}$ for operation. Whereas the first lidar housing is built out of PETG, later systems benefit from carbon fiber reinforced plastics. By iterating the construction and design, later systems contain improvements such as upgraded seals, heating of the hatch and a special structure for transportation by helicopter. The IAP has manufactured all three lidar in house within approx. one year whereas the Alexandrite lasers are built by the ILT. In Figure 1, on the right side the most recent EULIAA-UV2 is shown after installation at the Sphinx station of the High Altitude Research Station, Jungfrauoch, 47° N (HFSJG) at 3580 m altitude.

All EULIAA units benefit from the next generation alexandrite laser, which allows intra-cavity SHG to the UV for the second and third system whereas the first system is working at the fundamental wavelength. The spectroscopic approach is further advanced compared to VAHCOLI. The optimized and 3D-printed telescopes include various measures for reducing seeing at day is patent pending. Besides reducing the impact of seeing on the measurements at high solar elevation measurements, we demonstrated observations as close as 2° from the sun. The first system has been in unattended maintenance free operation for 10 months now. We tested the second system, EULIAA-UV1, operating at the iron resonance line (386 nm) a few days after the final assembling at OHP, 44° N, France for 10 weeks and currently transfer it to Payerne, Switzerland. The third system, EULIAA-UV2, is especially built for helicopter transport. Again, we transported and installed the lidar only a few days after final assembly at HFSJG. Both UV-lidars have been built and applied without test phases even though we integrated a novel UV laser and receiver technology. Both UV lidar are not optimized for signal strength or spectral resolution so far. A major goal of the project is the demonstration for a future European network of lidars, which requires finally assembling such lidars in short time, aligning them in the laboratory and applying it right afterwards at remote sites.

All three systems achieve continuous operation with minimal or no maintained work after installation. The major maintenance work on site has been refilling the chiller two or three times because of remaining air in the system. Moreover, all three systems have survived the transportation with aligned optics and operation was possible within a few hours after arrival. We also note that the Alexandrite laser has not needed any re-alignment and survived the transportation as well as unavoidable power breaks on site. During transportation as normal cargo, the system is not temperature stabilized. At OHP, the chiller failed because of a very short power break during a thunderstorm at the weekend and it was only possible to reestablish cooling on the next working day manually. The integrated emergency shutdown for such scenarios protected the lidar as planned. Nevertheless, overheating to $\sim 45^\circ$ caused by the sun and hot outside condition at OHP occurred. Nevertheless, measurements continued afterwards without any realignment with identical signal strength and without being even in thermal equilibrium as soon as cooling was established again.

Whereas challenging cold temperatures and winds occur in wintertime on top of the mountain at 69° N at ALOMAR, hot temperatures as high as 40° is not uncommon for OHP during day. The lidar at HFSJG on the top of the building is in particular facing strong winds, icy conditions, and frequent thunderstorms at an altitude of ~ 3600 m, which affects cooling. Already during the first measurements, the open hatch has survived 200 km/s wind gusts caused by local turbulence at the edge of the Sphinx building and measured by the integrated weather station as visible in Figure 1.

All three systems use identical subsystems including the chiller, which we engineered for all climate conditions and altitudes. In general, the chiller is part of the system as shown in Figure 1 on the left side but sometimes installed elsewhere for different reasons. At the HFSJG, stones for an increased weight have replaced the chiller whereas we moved the chiller into the building avoiding icy conditions. At OHP, ALOMAR and Payerne the chiller is part of the system, which simplifies installation. The design of the lidar ensures operation at all conditions and can be adapted to local environments if required.

3. DOPPLER MIE WIND AND AEROSOL

By combining a pulsed laser with a few MHz linewidth and two high finesse interferometers, it becomes possible to suppress very efficient the Rayleigh background leading to a solar blind Doppler-Mie lidar. Such a system is capable of measuring wind and aerosol 24/7 with high resolution up to roughly 30 km altitude 24/7 only limited by weather conditions. The observed spectral width of EULIAA-IR1 is in the order of 10 MHz for Mie-scattering whereas the Doppler width of Rayleigh scattering is ~ 1.4 GHz at this wavelength depending on temperature [3]. As consequence, the Rayleigh background below the Mie peak decreases by two orders of magnitude whereas the Mie signal is transmitted to a large degree. Besides a more classical analysis of the obtained spectrum, we built EULIAA as spectroscopic system for the variable atmosphere with the capability of signal decomposition. Once we know the instrumental properties, higher spectral resolution is achievable by post-processing resulting in a 10 times higher spectral and spatial resolution simultaneously. Whereas the long pulse of ~ 150 m of the alexandrite laser limits the spatial resolution for a classical spectral analysis, signal decomposition can be used to push the resolution down to 10 m. At the same time, the spectral resolution increases down to ~ 1 MHz, which is in particular valuable for the measurements of the Doppler broadening occurring during Mie scattering. An example of a measurement of Doppler broadening and other future applications is given by [5].

In Figure 2 we show a comparison of classical analysis on the left side versus signal decomposition on the right side. The increase in altitude resolution with signal decomposition is still visible here for the clouds even though the coarse resolution does not allow for fine details. Still the difference is obvious by comparing thin cloud structures. In particular, both methods show the same overall structures including gravity waves in the stratosphere. We still can measure the wind up to 20 km altitude within 16 sec /150 m in the presence of thin clouds including the wind below/above and within the cloud.

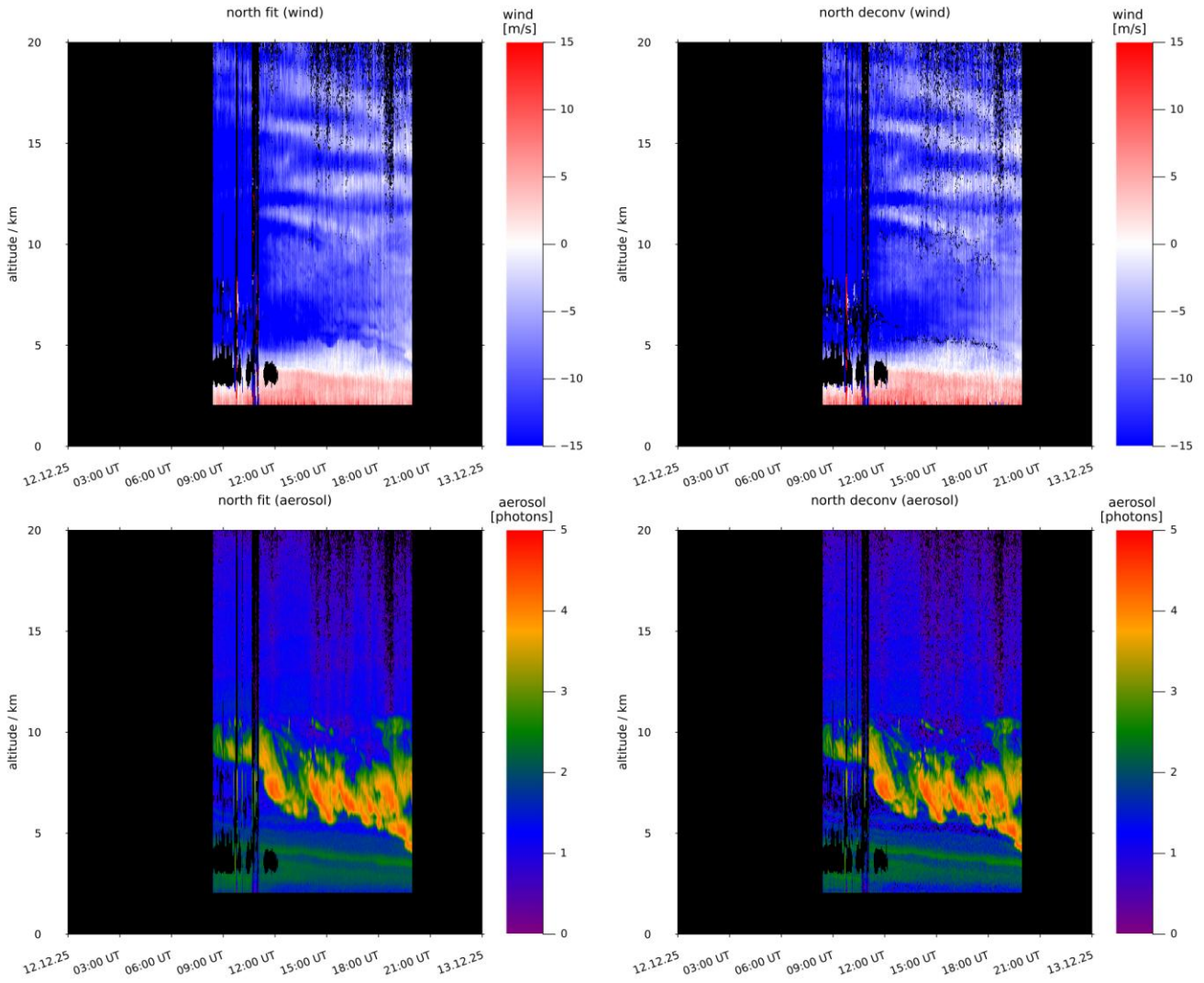


Figure 2. Left panels: Classical analysis of wind and aerosol with a spectral analysis. Right panels: Signal decomposition with afterwards reduced altitude resolution of 150 m for a direct comparison of both methods at a resolution similar to the pulse length of the pulsed laser. The lower panel shows the Mie signal as photon counts after subtracting the Rayleigh signal from the spectra at the same altitude. A comparison of wind and aerosol shows immediately that less than 10 photons from Mie scattering is sufficient for Doppler-Mie wind measurements.

The example here shows already that wind and aerosol are observable at any altitude replacing Doppler Rayleigh wind measurements entirely in the altitude range from ground to 25-30 km altitude. We have chosen an example from Alomar 69° N with clouds as a worst-case scenario. Whereas it is commonly believed that Doppler-Mie wind measurements do not work at all in clear sky conditions, the lidar at ALOMAR routinely measures wind at any time of the day and season at this location without any gaps. We can also measure wind below, within and above clouds as long as the transmission is sufficient. With longer integration, the aerosol load in the stratosphere limits the altitude range towards the topmost heights. Nevertheless, most measurements in the Arctic cover the whole atmosphere from 2-25 km and often up to ~30 km altitude, with longer integration as we will show now.

4. A TECHNOLOGY FOR A FUTURE SPACE MISSION

The capability to measure aerosols with high vertical resolution at the same time as the Doppler wind from Mie scattering with high resolution in the stratosphere is a unique capability. Currently the lidars of the two space missions, Aeolus and EarthCare, address either wind or aerosol from space. From the perspective of EULIAA both missions are limited by the short pulses of the Nd:YAG laser with corresponding broad laser line width. The short pulse limits the achievable spectral resolution finally by the Fourier-transform limit. In addition, comparable low finesse interferometers are used which are not stacked for maximum blocking of the solar background and Rayleigh scattering. EULIAA uses two stacked interferometers with a finesse of ~ 80 und ~ 150 for Doppler-Mie and additionally operates in a deep Fraunhofer-line for reduced solar radiation. The achievable spectral resolution of EULIAA for Doppler-Mie with signal decomposition is two orders of magnitude higher compared to Aeolus. The stacked high finesse interferometers with only 7.5 MHz spectral width for Doppler-Mie block solar radiation completely. Since no camera is needed, single photons are obtained at 1 m time of flight measurement and therefore with a resolution well below the pulse length of the laser. The background at daytime for Doppler-Mie is finally only given by the detector dark count in the order of 5 Hz. High altitude resolution is required for signal decomposition. Similarly, a large number of frequency channels are required. Major differences exist in the properties and capabilities of EULIAA compared to Aeolus. We achieve the narrow laser line shape of ~ 3 MHz with a long laser pulse, which limits the altitude resolution for a classical spectral analysis. For signal decomposition, the concept of a laser line shape is not sufficient anymore and meaningless. The time resolved measurements of the laser pulse shows a frequency chirp, which broadens the laser line shape during emission whereas the instantaneous emission at any time is close to the Fourier-Transform limit with less than 1 MHz. The laser must be treated in the analysis with a complex mathematical model with 11 parameters as well as the receiver must be characterized for the light path from the atmosphere in detail. Finally, the resolution in altitude and frequency is given by the post-processing and not by the properties of the filter and pulsed laser anymore.

Compared to the Aeolus lidar we achieve much higher resolution for wind at all altitudes for both analysis methods [6]. Compared to the EarthCare lidar the Rayleigh background is rejected to a much higher degree, allowing the observation of otherwise invisible aerosols in the troposphere and lower stratosphere at any time and at all altitudes. Beyond the capabilities of the technology of Aeolus and Earthcare is a direct measurement of the Doppler broadening of the Mie peak, which is currently under development and not discussed here. EULIAA measure also depolarization, which is also not shown. The additional observation of the metal layer (K or Fe) and aerosol (NLC) at 80-100 km altitude extend the capability of this technology further. More possible applications of this technology are described by [5].

EULIAA is not a demonstrator for a future space lidar and indeed optimized for Doppler-Rayleigh and Doppler-resonance rather than Doppler-Mie. Nevertheless, the compact and low-cost lidar with only 1.5 W average laser power and 20 cm lens telescopes built with less-than-optimal efficiency already achieves high performance. The typical data product in real-time is accessible for Alomar on the public website <https://euliaa-web.ch-meteoswiss-euliaa.fewcloud.host> whereas signal decomposition shown here is under development for improved capabilities and will be added in the future.

For a demonstration of the altitude range accessible by Doppler-Mie, we use as a reference a resolution of 20 min / 150 m, which is a typical resolution for ground-based measurements and show the analysis of signal decomposition for both wind components. EULIAA changes every four seconds the FOV looking into different directions including also a depolarization mode. By cycling through four different modes, we use only 25% of the time for a Doppler wind/aerosol measurement in a single direction. The standard resolution of 20 min / 150 m shown here refers therefore to a 5 min integration for each wind component obtained in a 20 min window. With this resolution EULIAA-IR1 achieves most of the time an altitude range approaching 30 km even at polar regions year around.

Figure 3 shows the horizontal wind for EULIAA-IR for a measurement of about 2 days with two different resolutions. Gravity waves in the stratosphere are obvious here and the phase propagations can easily be tracked throughout the whole period. The topmost altitude is slightly below 30 km for 5 min / 150 m integration per FOV, and the overall conditions of this day are calm. Due to single decomposition, thin layers caused e.g. by gravity waves become more prominent since the resolution for wind increases similar to the example before with clouds. This measurement is during polar summer with the sun always above horizon on a typical clear sky day and therefore low aerosol load.

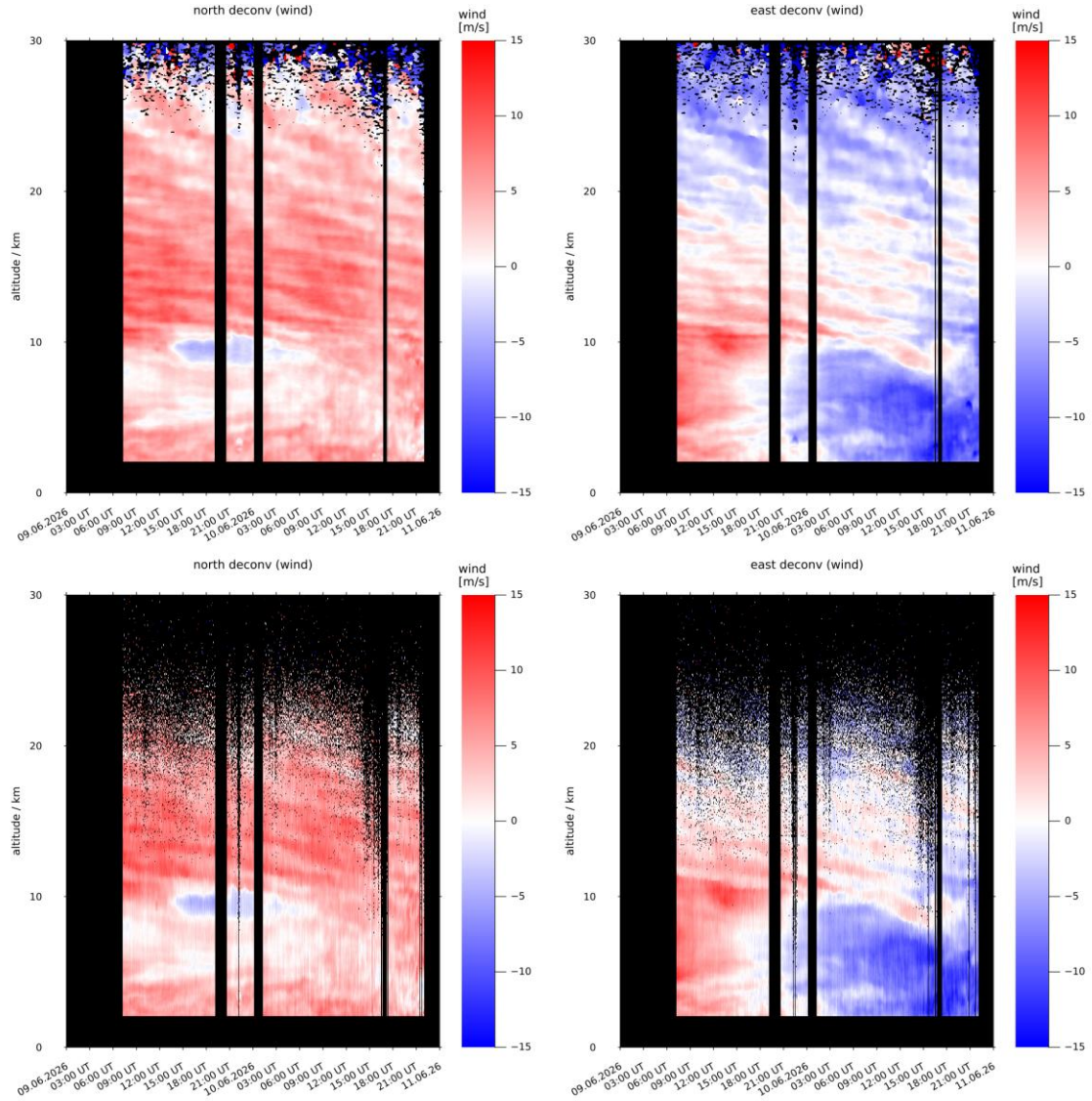


Figure 3. Horizontal wind measurement over 2 days (9.-10.6.2026) with EULIAA-IR at ALOMAR, 69° N at polar summer. With long integration, the measurement approaches 30 km altitude independent of the solar elevation. Integration per FOV in the two upper panels is 5 min /150 m. The lower panels show the same data set with 16 sec /150 m. We calculated both examples with signal decomposition

By integrating 16 sec rather than 5 min and therefore 20 times shorter integration, the upper part is lost, and the altitude range is limited to ~20 km similar to the first example with clouds. The gravity waves are still visible, and the overall structure is identical. The uncertainties are still below 1 m/s up to ~20 km altitude. Again, we achieve Doppler-Mie wind measurements at all altitudes regardless of the short integration and clear day conditions. We can restore the altitude range by reducing the altitude resolution similar to Aeolus. Figure 4 shows the same data set again but now derived from the fit rather than deconvolution because at poor vertical resolution this is not required. With a resolution of 16 sec / 1000 m the

altitude range is to a large degree restored and similar to the longer integration. As consequence, smaller scales are rejected but large-scale gravity waves are still visible. Since the resolution is given by data analysis only and not by data acquisition higher resolution in the troposphere below 150 m is achievable by changing parameters.

A spaceborne lidar can be optimized in lidar geometry and efficiency, therefore achieving a higher altitude range without scaling the laser power. A ground-based lidar also loses signal in the troposphere resulting in a lower signal strength in the stratosphere. The signal in the stratosphere, however, above the Junge layer is the most challenging part of the measurement. For a spaceborne lidar the eye-safe UV-version is required. The two EULIAA-UV lidar will be optimized in the future for higher performance similar to the IR-lidar in the past but are already able of Doppler-Mie wind and aerosol measurements with lower resolution. With intra-intra-cavity, SHG the pulsed laser has already similar efficiency and pulse energy compared to the IR version [7,8]. Optimized interferometers are under development and better alignment/optical improvements are required to regain the signal. Theoretical calculations of the achievable efficiency show that a similar signal strength for UV is within the reach of nowadays technology.

5. METALS IN THE MESOSPHERE: SPACE-DEBRIS

Whereas Aeolus and Earthcare focus on the lower atmosphere, EULIAA additionally measures aerosols such as rocket exhaust in the middle atmosphere or NLC (aerosol) in the mesosphere at ~85 km altitude. Designed as a resonance lidar and operating in a deep Fraunhofer line with excellent blocking of the solar background, small field of views and a novel telescope design EULIAA can observe the metal layer at daytime in the mesosphere. So far, we lock only EULIAA-IR1 onto the resonance line of potassium whereas the UV-version does not have a similar technology for iron. Still, we observe the metal layer by manual tuning to the resonance line once with the disadvantage of slow drifts around the center of the atomic line. We achieved stable operation with ~600 hours of operation on the first test of such an UV lidar at OHP including a 12-day continuous operation. The second UV lidar at HFSJG has successfully measured during 41% of the time during the first 4 weeks after installation without any maintenance work or realignment. Figure 5 on the right side shows a triple Fe-layer as observed from HFSJG at night for all three FOV. At Polar Regions, we can additionally observe NLC in summertime, which is challenging because of the low signal strength and high solar background at day. The left panel of

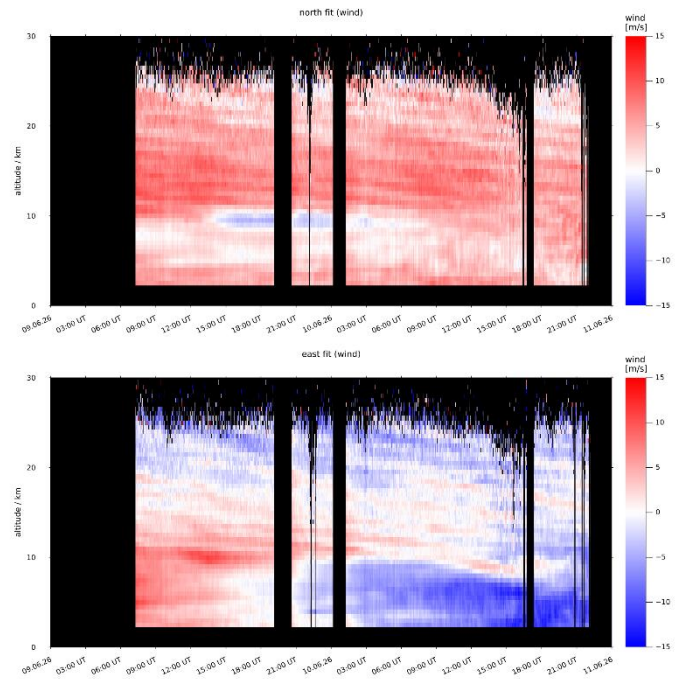


Figure 4. Restoring the altitude range by reducing the resolution to an integration of 16 sec /1000 per FOV.

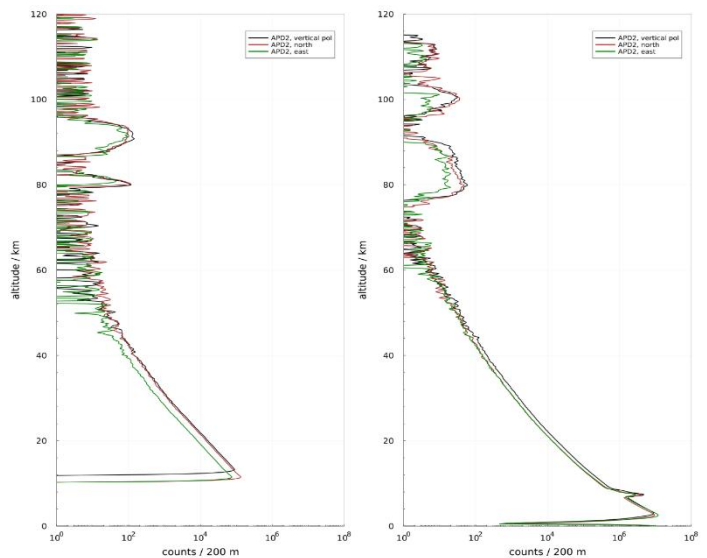


Figure 5. Mesospheric observations of aerosol and metals with EULIAA-IR1 and EULIAA-UV2 in three directions simultaneous. Left side: potassium layer at 90 km altitude with NLC below the layer. Observed at an average solar elevation of 19° at day at ALOMAR, 69°N, 5.7.2026, 04:36 - 04:48 UT. Right side: Tripple iron layer in the mesosphere and lower thermosphere observed from HFSJG, 47° N, 8.8.2026, 20:00 - 21:00 UT at an average solar elevation of -15°.

Figure 5 shows an NLC observed in all three directions by EULIAA-IR1 with the potassium layer above. A future space-borne lidar with extended altitude range locked to an atomic line can additionally observe resonance scattering in the mesosphere as has been discussed by [9]. At the same time, the middle atmosphere is accessible allowing observations for rare events such as rocket exhaust, volcanic eruption, or even meteor trails with a single instrument. Since the signal in the middle atmosphere is low compared to the troposphere, sampling the signal about the full altitude range does not contribute much to the raw data. In that way a single space mission can extend the altitude range and scientific impact by extending the measurement range to the mesosphere including resonance scattering.

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