EMORAL – mobile Mie-Raman lidar with fluorescence, polarization and water vapor observational capabilities for satellite Cal/Val field campaigns

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Abstract. ESA MObile RAman Lidar (EMORAL) was developed with the objective of participating in Cal/Val campaigns for ESA Earth Observation Programmes missions. Upgraded several times, current configuration and functionalities, especially broadband fluorescence and water vapor measurements together with wavelength-dependent polarization, backscattering and extinction coefficients observations, place EMORAL in the forefront of the modern lidar developments. Highly desirable state-of-art ensemble of near-real-time observations wascollected in different areas (urban, industrial, rural, peatland, mountains, flatland), thus providing exclusive sets of quality-assured high-level data products. Implementation Quality Assurance tools and Single Calculus Chain data evaluation schemes of Aerosol Clouds and Trace Gases Research Infrastructure (ACTRIS) contributes to lidar smooth operation and derivation of high-quality, ACTRIS approved data. Moreover, EMORAL effectiveness to obtain new data products such as fluorescence backscatter coefficient and fluorescence capacity in demanding environments is demonstrated, e.g. within polluted city of Wrocław, Poland, suburban biomass-burning affected Măgurele, Romania, background urban outskirts of Vilnius, Lithuania, as well as extremely clean coastal Orašac, Croatia. The knowledge gained from operating the lidar in different conditions and identified recommendations will drive further advancements and ensure its continued successful operation in future campaigns.

Keywords: EMORAL, lidar Cal/Val, aerosol, fluorescence.

1 Introduction

The development of the EMORAL (European Mobile Raman Lidar) system commenced in 2007, driven by a set of specific objectives. Its primary purpose was to actively participate in campaigns across Europe, contributing to the advancement of European expertise in the domain of Calibration and Validation (Cal/Val) campaigns for Earth Observation Program (EOP) missions. Additionally, the development aimed at establishing and sustaining a vital competence within the European Space Agency (ESA), focusing on lidar technology and know-how.

The EMORAL system has been developed to serve as a platform to test and refine atmospheric lidar concepts and technologies, ensuring their effectiveness and reliability in real-world scenarios. Furthermore, the provision of comprehensive datasheets was a key aspect, enabling scientific research and supporting various ESA activities.

Over the years, the EMORAL lidar has undergone several upgrades to enhance its capabilities. In this paper, we specifically focus on the implemented in the last five years lidar upgrades that were conducted to vast extent within the ESA funded Polish Radar and Lidar Mobile Observation System (POLIMOS) activity coordinated by University of Warsaw (UW). These upgrades represent the latest advancements and improvements made to the system, enabling it to operate at an even higher level of performance.

2 EMORAL Upgrades

2.1 UPGRADES I

Between September 2017 and March 2018, the EMORAL lidar underwent the first significant upgrades. The mobile platform was enhanced with a new Iveco van and its several modifications, including among others an additional air conditioning, an industrial power cable wiring, and a manual roof-hatch.

The lidar itself received a redesigned transceiver built by Raymetrics (Greece). The lidar is incorporating a new more powerful Nd-YAG laser, (SpitLight 400, InnoLas, Germany) operating at 1064 nm (nominal 112 mJ), 532 nm (nominal 103 mJ) and 355 nm (nominal 128 mJ), with a repetition rate of 10 Hz and pulse length 5-7 ns,a smaller size Cassegrain telescope with primary mirror of 300 mm, and an adjustable FOV within 2 to 3.6 mrad. We upgraded also capabilities of the detection unit with 16-bits transient recorders (TR40-160, Licel, Germany) used for recording signals by PMTs simultaneously in photon-counting and analog mode, except 1064 nm (analogue detection with APD).

This core modifications to the lidar design allowed us to derive successfully at the main objectives, namely, we improved the minimal range of the overlap down to

~250 to 350 m, we increased spatial (height) resolution to 3.75 m, and thus improved the data quality, while maintaining the overall high lidar performance.

The upgraded wavelength separation unit (WSU) enabled the detection of signals at eight channels: three elastic Mie channels at 1064 nm, 532 nm, and 355 nm, two depolarization Mie channels at 532 nm and 355 nm, three vibrational Raman channels for nitrogen detected at 387 nm and 607 nm, and water vapor at 407 nm.

Developments included also other functionalities: an automated telecover mechanism, a rotation mechanism of the entire detection unit, an automated sliding system for polarizers during the polarization calibration measurements, an automated system for sliding filters for protection of Raman channels from the stray-light radiation, a CCD camera for monitoring and adjusting the outgoing laser beam, and also a system of several laser interlocks assuring a safe lidar operation. Those implementations increased the smoothness of the lidar operational and the measurement quality, due to easy application of the recommended Quality Assurance (QA) tests according to procedures of the Aerosol, Could, and Trace-gases Research Infrastructure (ACTRIS).

Furthermore, considering the operational needs in extreme conditions in Eastern European winter and summer, as well as in the demanding peatland environments, special provisions have been made by the University of Warsaw (UW). This included the installation of oil heaters for winter operation, building an insolation chimney to mitigate environmental effects (less air exchange, temperature stabilization), using an external UPS (uninterruptible power supply) for electronic system stabilization, adding a bug-blower to remove insects form the immediate vicinity of laser, and finally, including a sky-monitoring camera to monitor atmospheric conditions and overpassing aircrafts enabling alerts to lidar operator assuring safety.

Those upgrades were achieved through collaboration between different partners and staff at ESA-ESTEC, UW, LMU, NOA, and Raymetrics. They highly enhanced the capabilities of the EMORAL for comprehensive atmospheric observations. The lidar was then deployed within the POLIMOS activity in April-September 2018 and June-August 2019 at the PolWET site of Poznan University of Life Sciences (PULS) located over unique vast peatland environment in Rzecin, Poland and provided long-term observations resulting in several publications of interest to satellite research (e.g. methodology for synergic lidar, radar and microwave retrieval [1], atmosphere-ecosystem model with full set of data assimilation at peatland site [2], comparative study of mineral dust properties of long-range transported mineral dust form Sahara [3]).

During the year 2018 a pilot campaign was conducted on the short-term schedule for observations in large Polish city – Kraków, conducted at the premises of Jagiellonian University in collaboration with AGH University of Science and Technology. Observations revealed high usefulness of the use of EMORAL for dry-ran type short-notice operation in smog conditions influenced by long-range transport of biomass burning from North America and mineral dust intrusions from Northern Africa [4].

2.2 UPGRADES II

During the period from September 2019 to October 2020, a series of additional rather small technical improvements and upgrades were implemented for the EMORAL lidar in collaboration with Raymetrics (Greece). Then the lidar was operated with a specific focus on the campaigns related to the ESA missions conducted by the National Observatory of Athens (NOA) scientists; the publications for this period are pending.

After the lidar was returned back to Poland, a specific list of recommendations for changes was prepared by the POLIMOS Team and provided to ESA and Raymetrics. Several filed campaigns took place in different locations and environments in Poland (e.g. pollution observations in cities of Zabrze, Kraków, Wrocław, observations in rural areas of Białystok-Krynice, Mikołów, Głowno, Milówka, and Chwałki).

UPGRADES III

The latest upgrades were implemented in September 2022 with the primary purpose of introducing an entirely new fluorescence channel, marking a major advancement in the overall capabilities of EMORAL lidar (see Fig. 1). The wavelength separation unit was redesigned and changes were exerted by Raymetrics. Additionally, the oldest three PMTs were replaced to ensure the optimal performance in terms of signal acquisition. So as to enhance the safety during the lidar operation, a radar system for detecting the aircrafts and helicopters was installed. Furthermore, there were several improvements made to the van, e.g. including an additional insolation of the van doors and mounting a more powerful automated air-conditioning system to empower a more efficient temperature control; re-painting the van roof to remove time-generated corrosion. Note that the EMORAL has been also fully prepared for an unattended automated remote operation but we never use this option due to the internal OSH Regulations of UW (contracted lidar operator).

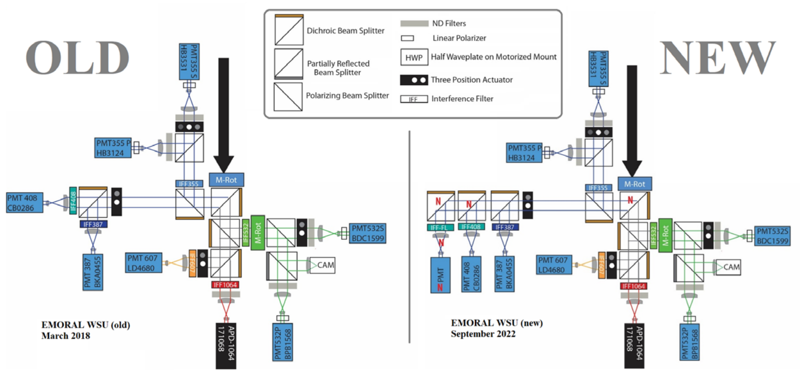

Fig. 1 Schematic design of Wave Separation Unit (WSU) of the EMORAL lidar between the Ist (here denoted as "old") and IIIrd (new) lidar upgrade.

The upgrade involved key developments to support the new fluorescence channel. The redesign of the wavelength separation unit was necessary, including replacement of a dichroic mirror at the very entrance of WSU, adding a new (long pass) beam splitter to separate 407 and 420-500 nm radiation, adding a broadband interference filer centered at 470 nm (420-500 nm), implementing a new eyepiece and PMT for fluorescence detection. Finally, adding a new Transient Recorder and high voltage supply unit for fluorescence channel (measuring in analog and photon counting modes).

3 EMORAL Intercomparisons, QA tests and optimization

3.1 Intercomparisons

Within the last 5 years, the EMORAL has undergone several direct intercomparisons with the reference lidars to ensure the stability of operating performance and the high-quality of observational data. The system was compared on the basis of the dedicated ACTRIS Quality Assurance (QA) tests, at the level of the lidar performance and at the level of the obtained data products.

After the Ist upgrade, the EMORAL comparisons were done in Warsaw in June 2018 against the ACTRIS reference lidar - POLIS (LMU) and PollyXT/NARLa (TROPOS/UW) lidar and in July 2019 against RALi (INOE) lidar and PollyXT (TROPOS/UW) lidar. There was several tests but no direct intercomparisons after the IInd upgrade in 2020. After the IIIrd upgrade, in September 2022, the EMORAL was compared at Măgurele against POLIS (LMU-MIM), RALi (INOE), and ALPHA (INOE) lidars; the example of joint observations is shown in Fig. 2.

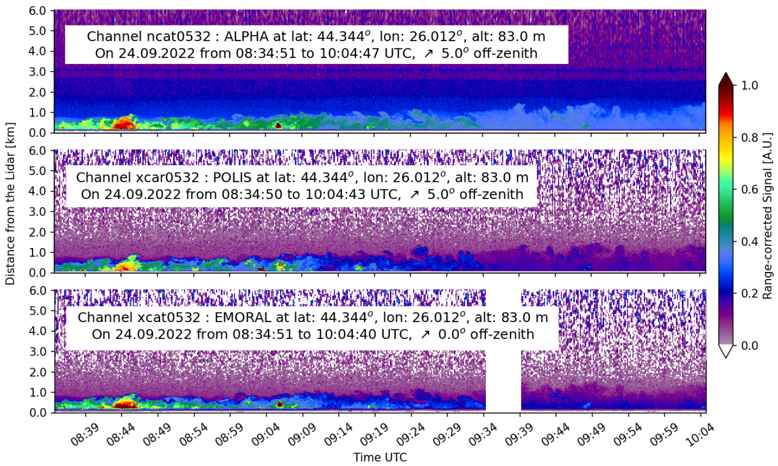

Fig. 2 Strong agreement for lidar comparison of ALPHA-INOE lidar (top, highest laser power, highest sensitivity, highest resolution), POLI-LMU (middle, ACTRIS reference lidar), and EMORAL-ESA/UW lidar at the ACTRIS Centre for Aerosol Remote Sensing at the MARS site of INOE in Magurele, Romania.

Note that the latest functionality of the lidar – fluorescence and water vapor data products, could not be intercompared with the ACTRIS reference lidars, as none of them possess this unique, although important capabilities. So far there are no plans for a direct intercomparisons but they could be done against the LILAS lidar of University of Lille, France [5] . Conducting such a comparative study can be highly recommended to be done with the aim to underline both the advantages and limitations of the different fluorescence wavelengths used by these two systems.

3.2 Result of QA tests and optimization

Rayleigh Fit

Initial misalignment of the system was observed from the result of Rayleigh fit, indicated by losing signal in the far-field and too much signal in the near-range (see Figure 3, top). The issues were resolved by performing lidar alignment using the CCD camera for monitoring laser beam installed into the EMORAL lidar (Fig. 3, bottom).

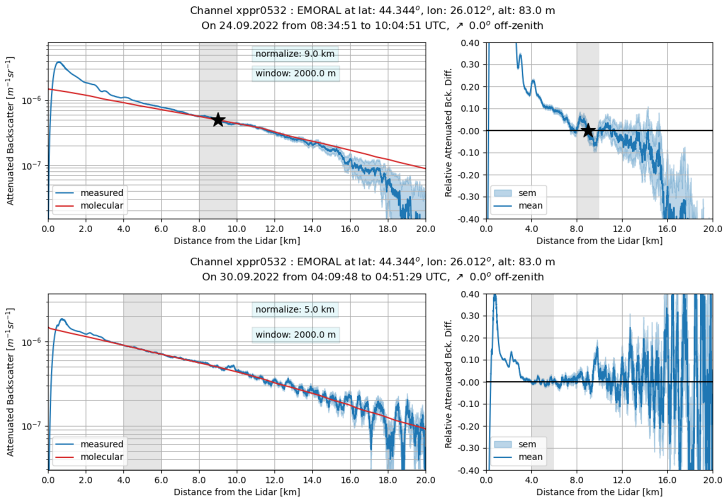

Fig. 3 Rayleigh fit for channel 532, initial misalignment (top) and corrected alignment (bottom).

Telecover Test

The automated telecover mechanism installed in EMORAL allows for fast check of the lidar alignment and for the efficient optimization of the overlap between the full field of view of the telescope and the three emitted laser beams, so as to achieve the lowest possible limit for the start of the overlap range; an example is shown in Fig. 4.

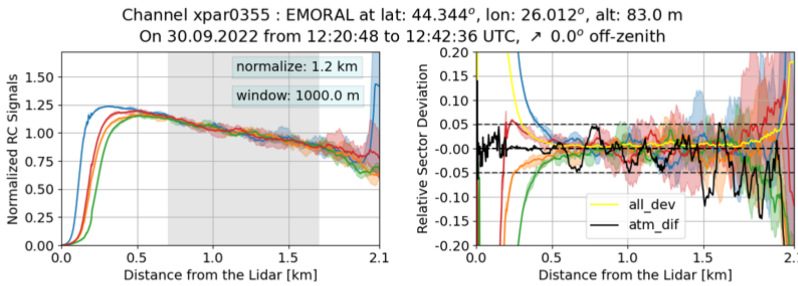

Fig. 4 Telecover test result at the channel 355 nm of the EMORAL lidar.

Depolarization calibration

The depolarization calibration was done in a semi-automated way several times during the campaign with very good results for both 355 nm and 532 nm channels; this even without the correction of the so-called GHK parameters (see example Fig. 5).

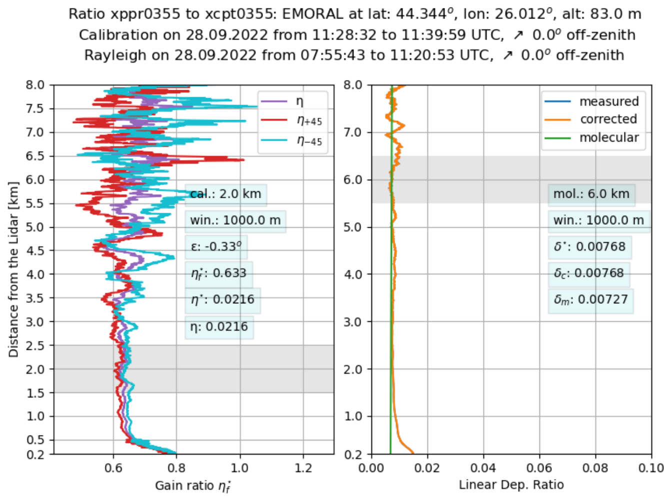

Fig. 5 Depolarization calibration result at 355 nm channel of EMORAL

4 EMORAL field campaigns

The EMORAL lidar took part in the vast range of the filed campaigns aiming at different research topics. The Ecosystem-Atmosphere campaigns in the peatland environment in Rzecin, Poland (2028, 2019) were aiming at assessment of the influence of aerosol abundance and properties on ecosystem functioning and growth production [2].

The Agriculture Dust campaigns had several objectives: capturing agriculture dust events, examining the properties of aerosols derived from agricultural dust as compared to mineral desert dust. They were conducted in Chwałaki (2021) and Głowno (2022), Poland. A methodology for comparing satellite and ground-based data with satellite observations from Sentinel 3 and 5P was developed and tested with data collected in different locations. The properties of agriculture dust particles were found to significantly differ from Saharan mineral dust particles [3].

The Trans-Pollution campaigns focused on examination of local versus long-range trans-border pollution, combination of in situ and remote sensing data, and assessment of the warm vs cold season in background urban environment of Vilnius, Lithuania (2022, 2023). These results revealed an increase in aerosol optical depth attributed to pollution transfer, as well as notable differences in surface/layers/column properties. Moreover, significant insights were gained into the optical and microphysical properties of the observed aerosols [4].

The Smog campaigns focused on investigation of the wintertime smog aerosol optical and microphysical properties in most polluted Polish cites, Zabrze (2021), Kraków (2018, 2022), and Wrocław (2022). Some of the observations in summertime allowed for estimation of the properties of photosmog (Warsaw 2019).

The most recent campaigns, after September 2022, aimed at derivation of new data products: fluorescence backscatter coefficients (β_F) and fluorescence capacity (G_F). Thus, special efforts have been at University of Warsaw to develop new algorithms that enable synergistic evaluation of unique set of signals in the EMORAL being the only one in the world currently capable of providing such data. The campaign that were conducted in Bucharest, Romania (September 2022), Orašac, Croatia (October 2022), Wrocław, Poland (November 2022), and Vilnius, Lithuania (January-March 2023) yield promising first results, shown below.

4.1 Fluorescence Backscatter Coefficient (β_F)

Following the recent upgrade, EMORAL has gained the capability to obtain fluorescence backscatter coefficients (β_F; see Fig. 6); the product retrieval algorithm is under development (preliminary results shown). The introduction of this new feature yields several noteworthy features. High consistency of results was observed when comparing measurements taken on the same day. Expected variability has been captured for measurements taken in presence of clouds or highly abundant aerosol load. Extremely low aerosol load during Orašac campaign indicate very clean conditions at this costal site. Bucharest observations reveal high aerosol load due to biomass burning and agriculture dust. During Wroclaw campaign exotic conditions in highly polluted wintertime urban atmosphere were captured.

Overall, the upgrade of the EMORAL lidar system by including the fluorescence backscatter coefficients demonstrate promising capabilities. The high consistency of results, observable variability where expected, successful measurements during specific campaigns in different environments, collectively contribute to expanding our understanding of the lidar performance and its potential applications.

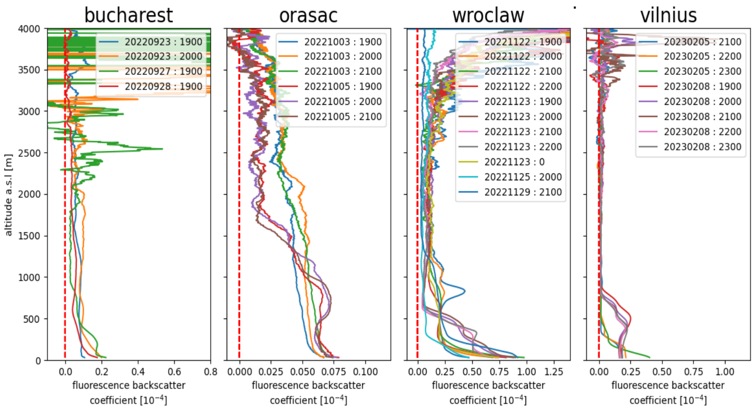

Fig. 6 Fluorescence backscatter coefficients (β_F) from EMORAL lidar in different environments: sub-urban in Romania, costal-rural in Croatia, polluted urban in Poland, and background urban in Lithuania.

4.2 Fluorescence Capacity (G_F)

Another new data product derived form EMORAL lidar is fluorescence capacity (GF; see Fig. 7), here calculated from the dataset obtained during Wroclaw campaign. The GF values obtained at 355 nm exhibit greater stability compared to other wavelengths used; this is clear advantage over retrieval scheme proposed in [5]. Profiles are obtained even below 500 m, allowing for detailed analysis of the lowermost atmospheric layers. Unique aspect of this data product in our approach is the combination of water vapor to correct the GF, thus enhancing the accuracy of the measurements. EMORAL stands out, as it offers such synergistic observations in multiple locations. There are no other lidar systems currently available that provided comparable range observations of fluorescence in such diverse settings and locations.

Although the EMORAL current data products have a lot of potential, there are still areas that could be optimized. The retrieval of particle backscatter coefficient profiles at 355 nm, 532 nm, and 1064 nm using the Single Calculus Chain (SCC) method may not be optimal for high aerosol load scenarios. Thus, resulting also in lower quality of the fluorescence backscatter coefficient and fluorescence capacity. Therefore, further improvements will be made to refine the retrieval process under such conditions.

Additionally, the noise handling is an area that requires attention. The currently applied approach utilizes moving average smoothing with a window size of 5-10 points (range bins of 3.75 m). Further refinement of the noise handling technique and tests of other approaches for denoising (e.g. Kalman filtering) shall even further enhance the accuracy and precision of the G_F data product.

Successful retrieval of fluorescence data products confirmed the presence of fluorescence signatures in the collected data, thus marking a significant achievement in the analysis and interpretation of EMORAL lidar measurements.

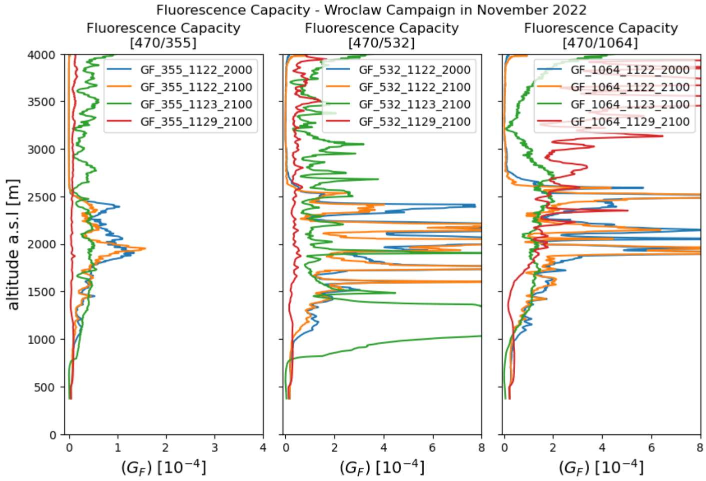

Fig. 7 Fluorescence Capacity (G_F) from EMORAL lidar during campaign in Wroclaw, November 2022.

6 Summary

Some recommendations for optimal use of EMORAL are specified in this summary.

First of all, attention to the transportation of the lidar, including proper packing, careful driving, and thoughtful route planning, is crucial to ensure its safety and integrity. Secondly, the campaigns require a team consisting of two operators and one data evaluator to ensure real-time data processing. Thirdly, importance of an isolating chimney is crucial, as it plays a vital role in enabling the 24/7 lidar's operation during both winter and hot summer conditions. Finally, the implementation of ACTRIS QA tests and semi-automated tools has proven to be highly beneficial in the smooth and optimal operation of the EMORAL lidar system. This assures that all lidar-derived aerosol properties are of highest quality.

Several recommendations have been put forward for further improvement. Most importantly, addressing signal disturbances. Particularly in the case of 1064 nm channel it involves collaborating with InnoLas to enhance electrical isolation of laser power supply and partnering with Licel to optimize detection with APD. It is also highly recommended to exchange the oldest five Transient Recorders (1064, 532-p, 532-s, 355-p, and 355-s channels) to reduce disturbances introduced by aging electronics.

Despite encountering challenging conditions, the lidar system has demonstrated its feasibility for use in the future ESA field campaigns, including Cal/Val activities. This highlights EMORAL capability to perform effectively even in demanding environments. The knowledge gained from operating the lidar system and the identified recommendations will contribute to further advancements and ensure its continued successful operation in future campaigns.

The ongoing development of the fluorescence backscatter coefficient (β_F) and capacity (G_F) data products for the EMORAL shows highly promising results. The current observations exhibit high consistency and observable variability within measurements taken on the same day. The lidar system has also demonstrated its effectiveness in low aerosol load environments, stability at 355 nm, obtainable at lower altitudes, and benefit from the synergistic input from water vapor for improved accuracy. While further optimization is needed for the high aerosol load scenarios and the noise handling, the EMORAL lidar system remains at the forefront, offering unique and comprehensive observations across multiple locations.

Looking ahead, the newfound capability of obtaining fluorescence data products opens avenues for future research and applications. One potential area of exploration is the utilization of fluorescence capacity in conjunction with depolarization ratio for aerosol typing, offering opportunities for even better characterization and understanding of aerosol properties.

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