The new MARTHA – a powerful lidar system for aerosol and humidity profiling up to the stratosphere

Benedikt Gast[(a)], Cristofer Jimenez[(a)], Karsten Hanbuch[(a)], Ronny Engelmann[(a)], Albert Ansmann[(a)] and Ulla Wandinger[(a)]
[(a)] Leibniz Institute for Tropospheric Research Leipzig (TROPOS)
Permoserstr. 15, D-04318 Leipzig, Germany
Lead Author e-mail address: bgast@tropos.de

Abstract: The stationary lidar system MARTHA at TROPOS has undergone a major upgrade. With a new diode-pumped laser, the average laser power has more than doubled. In combination with the large far-range telescope, this will allow us to profile the atmosphere from the ground up to the stratosphere. A new spectrometer with an extra telescope enables spectrally resolved measurements of laser-induced aerosol fluorescence, which shall allow unambiguous aerosol typing and the characterization of biogenic aerosol particles. The upgrade and the features of the new system are described and range-corrected signals from a first test measurement are presented.

1. Introduction

Aerosol particles influence our Earth's climate system in various ways by directly scattering and absorbing incident radiation as well as through aerosol-cloud interactions and other feedback mechanisms. To characterize aerosol optical properties, usually multiwavelength polarization lidars are used, which allow to retrieve key intensive properties such as depolarization ratio, lidar ratio or Angström exponent.

In the last years, a new lidar technology emerged – the fluorescence lidar technique. It extends the collection of intensive quantities by adding a new one – the fluorescence capacity [1]. Spectrometric measurements of laser-induced aerosol fluorescence have proven to allow for studying aerosol inside clouds [1] and for the correction of the systematic fluorescence error in water vapor measurements with lidar at low relative humidity [2]. Even the use of a single broadband fluorescence channel [3] allows for a rough aerosol classification. When combining the fluorescence capacity with the particle depolarization ratio, a discrimination between mineral dust, biomass burning, urban aerosol and pollen is possible [4]. For a first assessment, a broadband fluorescence channel was added to the Multiwavelength Atmospheric Raman Lidar for Temperature, Humidity and Aerosol Profiling (MARTHA) system at TROPOS, Leipzig. It has been measuring since 2022, enlightening the potential of the new technique. For example, measurements of aerosol fluorescence can even improve the aerosol detection by visualizing thin layers, that are not or only barely visible in the elastic lidar channels. During the 2023 wildfire season, several such thin smoke layers were observed over Leipzig at high altitudes, as well as above and even within cirrus clouds [5]. I.e., highly resolved fluorescence measurements could provide new insights into the stratospheric aerosol load and mixtures. To extend the altitude range for fluorescence measurements up to the stratosphere, a high-power lidar system is required. This was one motivation for a major upgrade of the MARTHA instrument, after more than 25 years of continuous operation [6,7]. The upgrade and the features of the new system are described in this contribution.

2. The new MARTHA

2.1. A new high-power laser

The first step of the upgrade was the installation of a new powerful diode-pumped laser. The SpitLight EVO IV from InnoLas Laser GmbH provides a laser pulse energy of about 1 J at a repetition rate of 100 Hz. This results in a performance of up to 100 W, if only the base wavelength of the laser (1064 nm) would be generated. Energy losses due to the second and third harmonic generation slightly reduce the maximum overall energy [8]. Standard operation parameters for the laser system are presented in Tab. 1. The energies at the three

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

wavelengths were measured with pyroelectrical sensors during the setup with the laser company. According to them, some percent of the second and third harmonic radiation get reflected at the beam splitters, which separated the different wavelengths to the energy sensors. So, during real operation (without these beam splitters) the energy will be approximately 5 % higher. Considering this, the overall laser power (sum over all three wavelengths) amounts to 89 W (i.e., 890 mJ at 100 Hz), which is still approximately twice the maximum power of its predecessor (42 W). This standard energy distribution was chosen to have similar power at the three laser wavelengths and also to prevent the optics down the optical path from damage. Especially the energy in the UV should not exceed 340 mJ to avoid burning the coating of following mirrors and lenses along the beam path.

Table 1. Standard parameters of the new laser

	Parameter	Value
	Beam diameter (FWHM)	6 mm
	Beam divergence	< 1.5 mrad
Polarization		
	1064 nm	horizontal
	532 nm	vertical
	355 nm	horizontal
Energies per pulse		
	1064 nm	302 mJ
	532 nm	280 mJ
	355 nm	281 mJ

2.2. (Optical) setup of the system

A sketch of the setup of the new MARTHA system is displayed in Fig. 1. The laser emits a beam with a diameter of approx. 6 mm (full width at half maximum, FWHM). This beam has to be expanded before it can be emitted into the atmosphere. Unfortunately, there was not enough space in the lab to place both the laser and expanding telescope in one line. Thus, two dielectric mirrors with high reflectance at all three wavelengths are used to direct the laser beam into the beam expander. The expanding telescope itself consists of two components. First, a 25-mm meniscus lens with a focal length of 100 mm widens the beam. Afterwards, an achromatic lens system of two 15-cm lenses collimates the beam again to nearly parallel. This lens configuration expands the laser beam with a magnification factor of 15. An elliptical deflection mirror (length: 21 cm, width: 15 cm) directs the expanded laser beam through a roof hatch and out into the atmosphere.

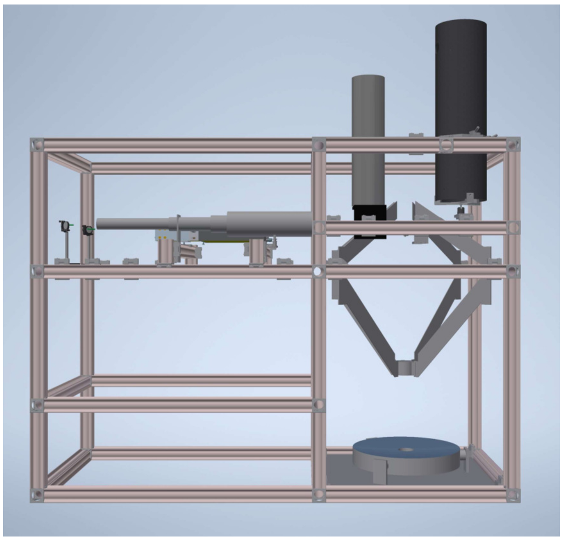

Figure 1. Side view of the laser (pulse) transmission unit and the receiving telescopes of the new MARTHA system. The wavelength separation unit is not shown.

An open issue is presently the careful housing of the outgoing laser beam to avoid that unwanted stray light enters the receiver unit.

The arrangement of the receiving telescopes is depicted in Fig. 2. The formerly coaxial system already possessed a main mirror with 80 cm in diameter and a near-range telescope with 20 cm in diameter and a divergence of 2 mrad. To measure spectrally resolved aerosol fluorescence, an additional 30-cm telescope was installed. It was designed to exclusively collect fluorescence spectra and was connected to a spectrometer. To avoid further obscuration of the main mirror and at the same time ensure a similar distance of all telescopes to the emitted laser beam, it was decided to change to a biaxial setup. The sending mirror and on each side one of the near-range and spectrometer telescopes were placed as far on one side of the main mirror as the dimensions of the roof hatch allowed to minimize the resulting obscurations of the main mirror.

The SP32-200-HR spectrometer from Licel GmbH uses 32 single photon counting channels to provide spectrally and time-resolved data. The Ultra-Bialkali photocathode can cover a wavelength range from 300 to 650 nm. A

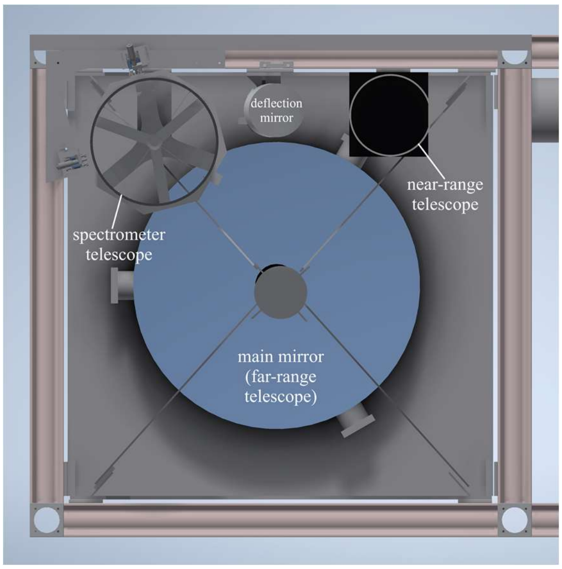

Figure 2. Biaxial setup and arrangement of the receiving telescopes of the MARTHA system.

grating with 1200 lines per mm allows a spectral resolution of 6.2 nm per mm, resulting in a wavelength span of 198 nm that can be covered with the 32-channel detector.

As the spectrometer uses an optical fiber as input, the spectrometer telescope had to be coupled into its fiber inlet. This was done by a 1-inch optical system that was designed for this purpose: Behind a 1-mm field stop, an achromatic lens with a focal length of 30 mm serves as objective. After a distance of 22.5 cm, a system of two achromatic lenses – one with a focal length of 40 mm and one with a focal length of 30 mm again – serves as ocular and ensures that the telescope mirror is imaged onto the entrance of the fiber inlet, which measures 2.7 mm in diameter.

3. Capabilities of the new MARTHA

Presently, the new MARTHA provides particle backscattering coefficients at three wavelengths, Raman measurements, extinction coefficients and lidar ratios at two wavelengths. The linear depolarization ratio is determined at 532 nm only and water vapor measurements are available at 407 nm. Laser-induced aerosol fluorescence is measured both with a broadband discrete fluorescence channel (444 – 488 nm) and spectrally resolved in a 198 nm broad wavelength range with the spectrometer.

It should be stressed here that the use of a separate telescope for the spectrometer is a big advantage, as it minimizes losses and allows to operate the spectrometer and the discrete detection channels in the same wavelength range (532 nm, 607 nm) simultaneously.

On a long-term basis, the new MARTHA will also provide extinction coefficients, linear depolarization ratios and Raman measurements at three wavelengths. Accordingly, an update of the far-range detection unit is planned for the near future. I.e., this may include the addition of further detection channels for multi-wavelength Raman and depolarization measurements and another discrete fluorescence channel at longer wavelengths.

The combination of the high laser power and the large far-range telescope shall enable us to profile the atmosphere over Leipzig from the ground up to the stratosphere, which will also be highly valuable for the ground-truthing of upcoming satellite missions like EarthCARE (Earth Cloud Aerosol and Radiation Explorer, [9]). The fluorescence capability can supplement and extend the applications of the previous Raman lidar measurements in different ways. At higher altitudes, the discrete fluorescence channels may help to study and characterize aerosol particles inside clouds and advance our understanding of aerosol-cloud interactions. In the (lower) troposphere, the spectrally resolved fluorescence measurements may enable an unambiguous aerosol typing. In particular, the assessment of mixture contributions of urban aerosol and pollen or biomass burning particles in the boundary layer may become more feasible. Furthermore, the fluorescence spectrometer will help to characterize biogenic aerosol particles, as well as to estimate their role in aerosol-cloud interaction processes. If possible, the distinction of different pollen types (or families) from their spectral fluorescence fingerprint will be attempted.

Up to now, only the fluorescence excited at the 355 nm wavelength was studied. But, when using a spectrometer in a spectral range up to 600 nm, also contributions of 532 nm excitation could be contained in the redder part of the measured fluorescence spectrum. In standard operation, the laser emits radiation at all three wavelengths, which could lead to the superposition of the fluorescence spectra excited at 355 and 532 nm, respectively. To separate both spectra, a wavelength separation of the initial laser beam is needed. Therefore, dichroic beam splitters that reflect the 532 nm and transmit the 355 nm and 1064 nm were designed. This will allow us to either send the UV and IR wavelength only or alternatively the green and the IR only. Thus, the contributions of both excitation wavelengths to the overall fluorescence spectrum could be assessed.

4. First (preliminary) measurements

At the moment, first tests with the new system are performed. Thus, up to now only some preliminary data of a first test measurement in the night of 7 to 8 March 2024 are presented. Fig. 3 shows the range-corrected lidar signal of the MARTHA far-range channels. As it can be seen, the signals are of good quality up to 20 km height. This underlines the potential of the new MARTHA system for the vertical profiling even of the lower stratosphere.

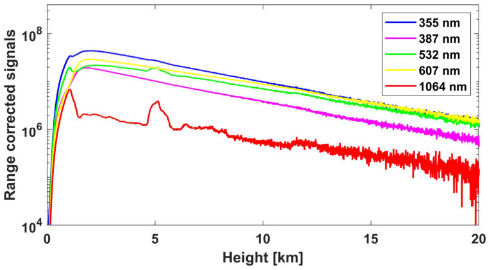

Figure 3. Range-corrected lidar signals averaged over the time period from 23:00 to 01:30 UTC on 7 to 8 March 2024.

5. Conclusions and outlook

After this major redesign, the new MARTHA system will be a powerful lidar reference station for long-term observations of aerosols up to the stratosphere. The fluorescence capabilities may improve the aerosol typing and characterization of biogenic aerosol particles. In combination with the high laser power, this will enable the detection and characterization of thin aerosol layers at high altitudes and advance our understanding of aerosol-cloud interaction processes. In the near future, the automatization of the system is planned to allow continuous measurements.

6. Acknowledgements

We acknowledge the funding by the Saxon State Ministry for Science, Culture and Tourism (SMWK).

7. References

[1] Reichardt, J., Leinweber, R., & Schwebe, A.: Fluorescing aerosols and clouds: investigations of co-existence. In EPJ Web of Conferences (Vol. 176, p. 05010). EDP Sciences (2018).

[2] Reichardt, J., Behrendt, O., & Lauermann, F.: Spectrometric fluorescence and Raman lidar: absolute calibration of aerosol fluorescence spectra and fluorescence correction of humidity measurements. Atmospheric Measurement Techniques, 16(1), 1-13 (2023).

[3] Veselovskii, I., Hu, Q., Goloub, P., Podvin, T., Korenskiy, M., Pujol, O., ... & Lopatin, A.: Combined use of Mie–Raman and fluorescence lidar observations for improving aerosol characterization: feasibility experiment. Atmospheric Measurement Techniques, 13(12), 6691-6701 (2020).

[4] Veselovskii, I., Hu, Q., Goloub, P., Podvin, T., Barchunov, B., & Korenskii, M.: Combining Mie–Raman and fluorescence observations: a step forward in aerosol classification with lidar technology. Atmospheric Measurement Techniques, 15(16), 4881-4900 (2022).

[5] Gast, B., Jimenez, C., Haarig, M., Ansmann, A., Engelmann, R., & Wandinger, U.: Fluorescence lidar improves the detection of (thin) aerosol layers. ACTRIS Science Conference (2024).

[6] Mattis, I., Ansmann, A., Müller, D., Wandinger, U., & Althausen, D.: Multiyear aerosol observations with dual-wavelength Raman lidar in the framework of EARLINET. Journal of Geophysical Research: Atmospheres, 109(D13) (2004).

[7] Mattis, I., Müller, D., Ansmann, A., Wandinger, U., Preißler, J., Seifert, P., & Tesche, M.: Ten years of multiwavelength Raman lidar observations of free-tropospheric aerosol layers over central Europe: Geometrical properties and annual cycle. Journal of Geophysical Research: Atmospheres, 113(D20) (2008).

[8] Boyd, R. W., Gaeta, A. L., & Giese, E.: Nonlinear optics. In Springer Handbook of Atomic, Molecular, and Optical Physics (pp. 1097-1110). Cham: Springer International Publishing (2008).

[9] Wehr, T., Kubota, T., Tzeremes, G., Wallace, K., Nakatsuka, H., Ohno, Y., Koopman, R., Rusli, S., Kikuchi, M., Eisinger, M., Tanaka, T., Taga, M., Deghaye, P., Tomita, E., and Bernaerts, D.: The EarthCARE mission – science and system overview, Atmos. Meas. Tech., 16, 3581–3608, https://doi.org/10.5194/amt-16-3581-2023, 2023.