Overlap-function Correction of Lidar-Derived Aerosol Optical Depth

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Abstract: We assess the feasibility of correcting the aerosol optical depth by measuring an overlap function from the combination of elastic and N_2/O_2 rotational-spectrum Raman signals in an advanced aerosol lidar. It is shown that very similar overlap functions can be derived from measurements taken in different days, leading to an extension of minimum range at which the aerosol optical depth can be measured. This opens the way to determining the aerosol extinction coefficient at ranges below the lidar full overlap with overlap functions measured in favorable conditions.

1. Introduction

A well-known limitation of lidar measurements at short ranges is the loss of signal caused by a partial overlap between the transmitted beam and the receiver field of view.

The minimum range can be hardware-extended by providing the lidar with a combination of far- and near-range channels, the near-range channels using small telescopes with short focal lengths, able to provide larger fields of view.

Alternatively, for advanced aerosol lidar systems with both elastic and Raman channels, the overlap function (the ratio between the power scattered by a scattering volume at a given range that reaches the photodetector, excluding transmission losses, and the power scattered by the same scattering volume that reaches the telescope aperture) of channels using large telescopes can be measured [1,2] and used to compensate the signal loss.

We compare two overlap functions obtained for the 355-nm channel of the EARLINET/ACTRIS lidar at Universitat Politècnica de Catalunya (UPC, Barcelona, Spain) from different measurements for the same nominal configuration. Very similar overlap functions are obtained, although they are not identical, because of the assumptions made in their retrieval. Also, possible unintended variations in the geometrical configuration (temperature-related expansions, change in the cross-section profile of the transmitted beam…) cannot be ruled out. The aerosol optical depth (AOD) measured by the lidar between a given range and the aerosol-free atmosphere range is assessed when using either of the two overlap functions in order to determine the minimum range at which the correction is trustworthy.

2. System

The UPC EARLINET/ACTRIS lidar is a 3β (1064 nm, 532 nm, 355 nm) +2α (532 nm, 355 nm) +2δ (532 nm, 355 nm) system with pure rotational Raman channels [3–5] and a water vapor Raman channel (407 nm), based on a Nd:YAG laser equipped with second- and third-harmonic generators.

In its current configuration, the lidar has a periscope made of two dielectric mirrors with multilayer coatings providing high reflectivity at the three emitted wavelengths, allowing the transmitted beams be collinear with the receiving telescope axis.

The main receiver collects the backscattered wavelength with a 14-inch diameter, f/10 telescope. The collected radiation is sent to a field lens that images the telescope aperture on a 3-mm diameter bundle of optical fibers with 0.12 numerical aperture. The bundle guides the radiation to a polychromator where a system of lenses, dichroic beam splitters and filters makes the radiation at the different wavelengths reach the corresponding photodetector [4], [6].

Although not relevant for this study, depolarization-measurement capability is provided by two small telescopes fitted with linear polarizers that can be rotated for calibration purposes [7]. A picture of the lidar optical head is shown in fig. 1.

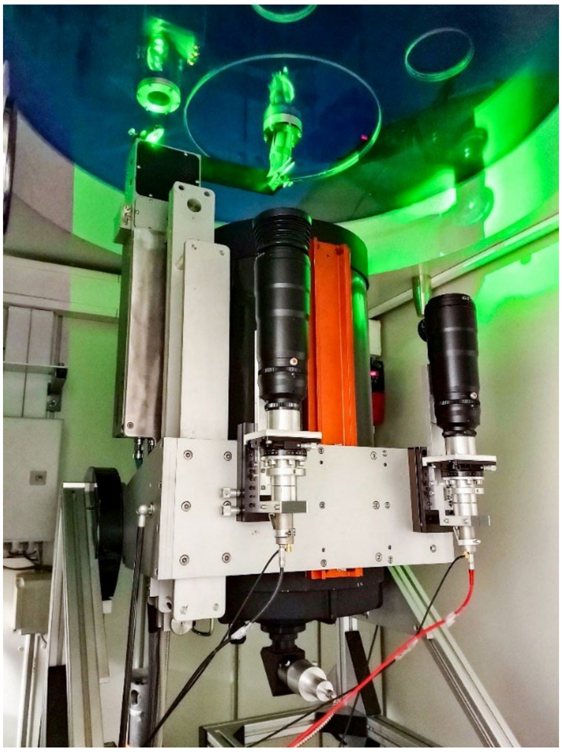

Figure 1. Optical head of the UPC EARLINET/ACTRIS lidar.

3. Overlap function retrieval

The overlap function has been retrieved by the explicit method of Comerón et al. [2], which gives identical results as the iterative method of Wandinger and Ansmann [1]. These methods require the assumption of the lidar ratio of the aerosols in presence during the measurement. The explicit method permits to show that the ratio of the retrieved overlap function with respect to the true one is given by

$$\frac{O'(R)}{O(R)} = \exp\left[-2\int_{R}^{R_\mathrm{m}} \Delta S_a(x)\beta_a(x)dx\right], \quad (1)$$

where R is the range above the lidar, $O'(R)$ is the retrieved overlap function, $O(R)$ is the true overlap function, R_m is the reference range used in the retrieval, which must be taken above all the aerosol layers, $\beta_a(R)$ is the aerosol backscatter coefficient and $\Delta S_a(R)$ is the difference between the assumed lidar ratio and the true one. For this reason, for the overlap function measurement very clear days were taken (18 January 2024 and 5 February 2024, with AODs measured at 340 nm by the UPC AERONET sun-photometer below 0.05 at the latest time in the afternoon on 18 January, and below 0.1 at the same wavelength for most of the day on 5 February, although a surge to 0.3 followed by a decrease is observed at the end of the afternoon; the measurements to retrieve the overlap function were carried out in the early hours of the night, starting between 18:00 UTC and 19:00 UTC) with no aerosol layering that could suggest aerosols of different origins and lidar ratios. The lidar ratio in the retrieval (35 sr on 18 January, 55 sr on 5 February, both values in the range of reasonable lidar ratios at 355 nm measured in Barcelona EARLINET/ACTRIS site) was chosen to approximately minimize the derivative of the overlap function with respect to range in the zone where aerosol still extends above the presumed full overlap. A smoothing procedure, described in [2], is used to suppress the measurement noise. Nevertheless, to prevent artifacts caused by smoothing in the zone of low overlap factors, where anyway the signal-to-noise ratio of the retrieval is high, the raw values obtained with no smoothing are used below 200 m. Figure 2 shows the overlap functions obtained from the combination of the 355-nm elastic channel and the 354-nm rotational Raman channel.

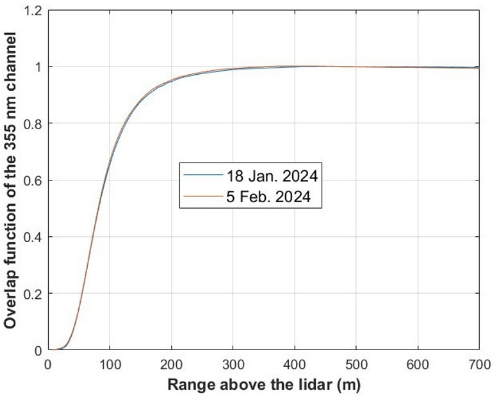

Figure 2. Overlap functions for the 355-nm channel obtained in two different days and atmospheric conditions.

4. Results

The effect of the correction by these very similar, but not identical, overlap functions on the measured aerosol optical depth has been tested on measurements carried out in February and March 2024.

The aerosol optical depth from a given range R at 355 nm is given by

$$AOT^{nc,c}(R) = \frac{1}{2} \ln\left[\frac{X_{Ra}^{nc,c}(R)}{X_{mol}(R)}\right], \qquad (2)$$

where $X_{Ra}^{nc.c}(R)$ is the background-subtracted measured Raman signal at 354 nm (note that for a rotational Raman channel at 354 nm, virtually no Ångström-exponent correction is needed to produce the AOD at 355 m). The superscripts *nc* and *c* stand for overlap “non-corrected” and “corrected” respectively. $X_{mol}(R)$ is the reference molecular signal the Raman signal has been fitted to. In our case, $X_{mol}(R)$ is derived using pressure and temperature data from the nearest in time (the next midnight in this case) radiosonde launched from Universitat de Barcelona at 600 m from the UPC lidar. For the non-corrected AOD, the Raman-channel data are used as is, while

$$X_{Ra}^{c}(R) = \frac{X_{Ra}^{nc}(R)}{O(R)}. \qquad (3)$$

As an example, the results of applying the two overlap functions to the data are shown for two different days. Figures 3 and 4 show the uncorrected and corrected (with the two overlap functions of fig. 1) AODs for measurements performed respectively the 1st of February 2024 and the 1st of March 2024. The uncorrected measurement shows a decreasing, non-physical behavior for decreasing range, starting approximately at 400 m (approximately the range ay which the full overlap in fig. 1 is attained). In both days, the corrected AODs follow closely each other (within thousandths of AOD) from high ranges until approximately 150 m. Below this range, further checks of the correct estimation of the overlap function (for example, the underlying hypothesis that it affects in the same way the elastic and the Raman channels might not be true) would be necessary.

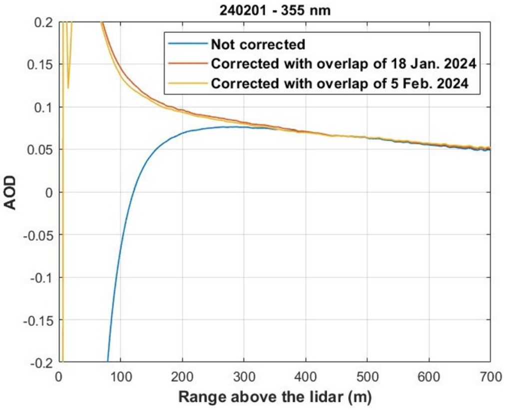

Figure 3. Uncorrected and corrected AODs for the measurement of 1 February 2024.

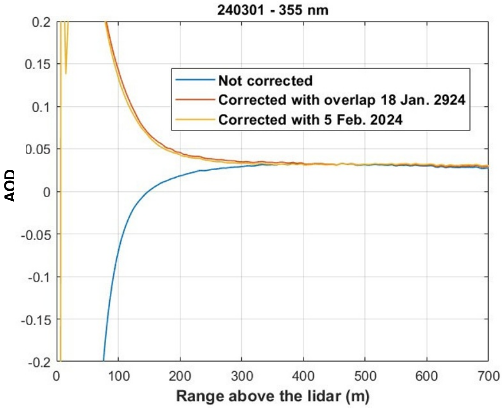

Figure 4. Uncorrected and corrected AODs for the measurement of 1 March 2024.

5. Conclusions

The feasibility of obtaining a stable overlap function for an advanced aerosol lidar under different, yet clear, atmospheric conditions has been tested. Very similar overlap functions at 355 nm have been retrieved from the combination of the elastic and rotational Raman channels of the UPC EARLINET/ACTRIS lidar in two different days. These overlap functions have been tested correcting the AOD measurements on different days. Very similar results are obtained below the full overlap (400 m) range, extending as low as 150 m. Further checks are necessary to assess the validity of these results (for example, comparison with a system with low full-overlap range) and, in particular, of the minimum range to which the overlap correction can be trustfully applied. A study of the effect on the retrieval of the extinction coefficient (minus the derivative of the AOD) must also be carried out.

6. Acknowledgements

The authors acknowledge the technical support of Joaquim Giner, Eric Vila and Rubén Tardío.

The use of radiosonde results is possible thanks to the Meteorological Service of Catalonia (Meteocat) and the Department of Astronomy and Meteorology of Universitat de Barcelona's Faculty of Physics.

The funding contribution of the H2020 projects ACTRIS IMP (grant agreement No 871115), ATMO-ACCESS (grant agreement No 101008004) and of the Catalan Regional Government grant 2021 SGR 01415, as well as the support of the Spanish Ministry for Science and Innovation to ACTRIS ERIC are gratefully acknowledged.

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