COMPARISON OF AEROSOL OPTICAL DEPTHS RETRIEVED BY AERONET, V-PROFILES AND ALICENET IN MESSINA

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1. Rationale

One of the goals of the EUMETNET's E-Profile initiative is to obtain a robust retrieval of aerosol extinction and mass out of the inversion of automatic lidar-ceilometer (ALC) profiles. While contributing to this activity, we found differences larger than expected (up to one order of magnitude) between the values of aerosol mass retrieved using the V-PROFILES and Alicenet algorithms when analysing data collected by the ALC (Alicenet/E-Profile) operating at Messina (Sicily, southern Italy) during the eruption of the Stromboli volcano on July 3, 2019. Going backward to explore reasons for these discrepancies, remarkable differences were already found in the first step of the V-PROFILES retrieval, that is, in the retrieval of the extinction coefficient profile (in fact, Alicenet computes mass out of backscatter profiles which are characterized by a lower error than extinction ones). The differences found between the two extinction profiles remained even using the same, fixed lidar ratio (LR, i.e. the coefficient to translate a backscatter signal into an extinction one) in both algorithms.

This report explores the performances of the two retrievals and possible reasons for discrepancies. To this goal, ALC and co-located Aeronet sun/sky-photometer data collected at Messina in early 2020 are exploited.

2. Methods

2.1 ALC inversions

Differences found in the Stromboli plume test case (even when using the same LR) suggested the observed dissimilarities in retrieved profiles may be due to the diverse calibration methods employed by Alicenet and V-PROFILES to obtain unattenuated profiles in absolute backscatter and extinction units.

Calibration of the lidar signal can be performed in aerosol-free regions, usually above 4km altitude, by matching the ALC profile against a reference molecular one (Rayleigh technique). In agreement with the E-PROFILE approach, Alicenet computes the signal calibration coefficient (CL) during clear-sky nights. Time-specific CLs are then interpolated via a Loess regression amongst adjacent night-time ones, and used to retrieve particle backscatter and extinction coefficients by means of a "forward" Klett method (e.g., Wiegner and Geiss, 2012). As noted by these authors, no particular trends were observed in the Messina CL values over a time-span of several months.

Conversely, the V-PROFILES approach searches for a reference molecular layer, generally between 4000 and 6000 m, where to calibrate each (night and day) inverted profile. It then employs a "backward" Klett method (Weitkamp formula) to derive particle backscatter and extinction coefficients. While tracking the ALC sensitivity changes during the day, this approach could suffer from daylight noise and might be more susceptible to calibration errors in the presence of elevated aerosol layers and/or clouds.

2.2 Datasets

The AERONET sun-photometer in Messina (Fig. 1) was not operating during the 2019, Stromboli eruption addressed in the test case. Therefore, in this analysis we focus on data from the ALC and the co-located AERONET sun-photometer collected in Messina in the four-month period January-April, 2020. This period also includes the transport over Messina of a minor eruption from Mt. Etna volcano (orange marker in Fig. 1), occurred on January 22, 2020. The volcanic aerosol layer was then located between 3000 and 4000 m MSL.
We thus compare the sun photometer-measured aerosol optical depth (AOD) to the ALC AODs (obtained as the integral of the aerosol extinction profile) as derived using both the Alicenet and V-PROFILES inversion procedures.

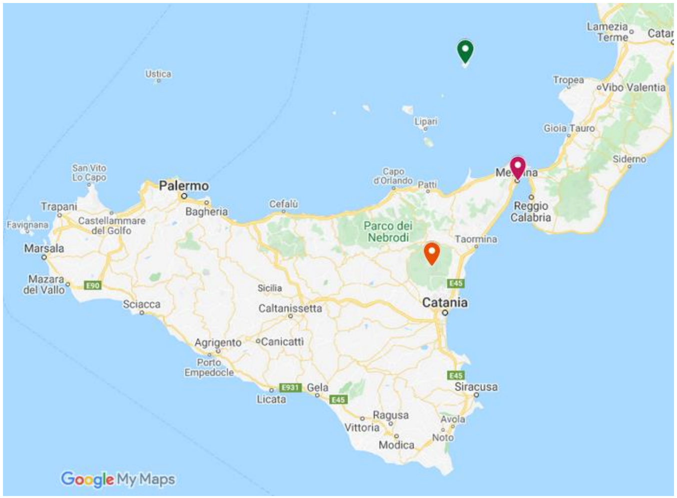

Figure 1. Map of Sicily, evidencing the Messina Alicenet/E-Profile and AERONET sunphotometer measurement site (violet marker), as well as the location of the Stromboli (green marker), and Mt. Etna (orange marker) volcanoes.

In particular, the following datasets collected in Messina are used here:

1. AERONET: a) AODs (L1.5, direct-sun data) extrapolated to the ALC wavelength (1064 nm) by applying the Angstrom formula to the sun photometer multi-wavelength AODs in the range 440-1020 nm; b) the Extinction Angstrom exponent (EAE, computed between 440 and 1020 nm) from L1.5, direct-sun data, and c) the 1020nm Lidar Ratio (LR) inverted by AERONET out of Almucantar observations. Data (b) and (c) are exploited to identify different aerosol types.

2. Aerosol extinction profiles (at 1064 nm) retrieved from ALC raw data using the Alicenet inversion algorithms. In particular, two different aerosol extinction dataset are obtained using, respectively: a) a fixed LR of 30 sr (chosen specifically for direct comparison with V-PROFILES, see below), and b) a variable, backscatter-dependent LR inferred using continental aerosol backscatter-to-extinction functional relationships (Alicenet retrieval model, Dionisi et al. (2018)), i.e. without any a-priori assumption of the LR value. In both cases, extinction data time resolution is 5 minutes. Only profiles

belonging to selected clear-sky, cloud-free intervals were employed. These were identified based on the analysis of noise from the 5-minute Alicenet retrievals and on visual inspection of the ALC images. This procedure led to 1310 simultaneous AERONET-Alicenet ALC measurements. To reduce the measurement noise, and for direct comparison with V-PROFILES, the data from Alicenet were also averaged at hourly intervals centered about the AERONET measurements.

3. AODs obtained by integration of the two Alicenet aerosol extinction profiles (LR=30 sr, and variable LR) described at point 2,

4. AODs retrieved by the V-PROFILES web site for the Messina ALC (employing a fixed LR of 30 sr, as recommended by Augustin Mortier as most suitable for Southern European stations). Since this dataset's time-resolution is 1 hour, for its comparison to AERONET measurements, the latters were averaged over a ±30' window centered about the V-PROFILES time.

   Overall, the averaging and cloud-filtering procedures led to 1310 AERONET-Alicenet, and to 197 AERONET-V-PROFILES simultaneous AOD pairs. Averaging the Alicenet data as the V-PROFILES ones (1-h averaging) and selecting coincident ones generated a common dataset of 193 profiles. Finally, an alternative filtering, applied to the AERONET data to select the most homogeneous sky conditions (see below), reduced the AERONET-Alicenet and AERONET-V-PROFILES AOD pairs to 161 and 110, respectively. All these various datasets will be addressed in the following sections.

3. Results

Results of the comparisons between ALC-derived and co-located AERONET AODs are shown in Figures 2-to-5 hereafter. ALC retrievals obtained employing LR=30 sr are presented first (Figures 2 and 3). Conversely, results obtained employing the Alicenet model LRs in the Alicenet retrieval are presented in Figure 4. Figure 5 shows the retrievals obtained by the Alicenet procedure applied to profiles averaged over the same times as V-PROFILES.
Comparisons are performed for both cloud-screened (AERONET Level 1.5 cloud-screened direct-sun data, and ALC cloud screening) and Almucantar-screened (AERONET inversion) datasets. This second screening is more stringent since AERONET Almucantar retrievals are only provided in homogeneous sky conditions. Since ALC and sunphotometer do not sample the same portion of the atmosphere (the ALC points to the zenith while the sun-photometer points to the sun and various sky portions), this further screening is assumed to avoid cases with presence of (undetected) thin clouds in the AERONET direct sun data and/or of inhomogeneous aerosol layers differently affecting the 'field-of-view' of the two instruments.

Aeronet vs. Alicenet-AODs using fixed LR = 30 sr

The comparison between the Alicenet-AODs using LR=30 sr, and the AERONET AODs is presented in Figure 2. Cloud screened and Almucantar-screened data pairs are compared in the left and right plot, respectively. To help the analysis, data points are color-coded according to the EAE (440-1020 nm) in the left plot and to the Aeronet-retrieved 1020 nm lidar ratio (LR) in the right one. Minimum EAE value considered in the comparison is set to EAE=0.6, that is the minimum EAE of the V-PROFILE dataset.

As previously mentioned, a lidar ratio of 30 sr was employed since indicated as good for southern European locations. As a matter of fact, according to results presented in Dionisi et al. (2018), we believe the most suited LR for European conditions to be LR=39 sr. Still, since the current V-PROFILE platform only allows for two LR options (30 and 50 sr), we opted for using LR=30 sr in this exercise. In Appendix A1, we address some further details concerning the choice of LR in various aerosol conditions across Europe and North Africa.

Results in Fig. 2 show that 71% of the Alicenet AODs fall within an interval of ±0.02 from the AERONET "direct sun" ones, i.e, within the sunphotometer calibration uncertainty (Eck et al., 1999). Still, a number of Alicenet points show a clear underestimation of the AOD with respect to the AERONET reference. In order to investigate the reason for such behaviour, data were colour-coded according to their EAE values. This information reveals that underestimation mostly appear in the presence of large particles (smaller Angstrom exponents) in the atmosphere. In fact, most of the large underestimated Alicenet-AODs pertain to a single Saharan dust advection day (17/4/2020). As addressed in Appendix 1, such cases would presumably be better retrieved using LR >> 30 sr.

In the warm seasons, fine particles (owing to their secondary origin) have usually low LR. However, in winter, small and absorbing particles (e.g., from combustion), are likely to contribute to an increase in the LR of the atmospheric aerosol. This is particularly evident in polluted areas. A minor number of cases of Alicenet underestimation in Fig. 2 pertain to large values of the EAE (1.5-2) and are possibly associated with wintertime, fine aerosol pollution.

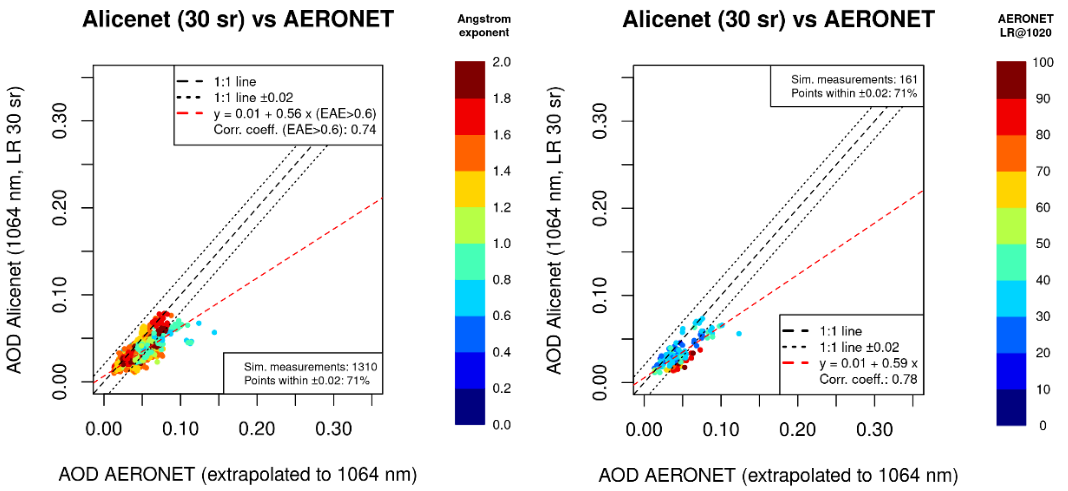

Figure 2. Scatterplot of 1064 nm AODs from Alicenet extinction profiles (using a LR = 30 sr) compared to AERONET L1.5 data (left) and Almucantar data (right). The colour scale indicates the extinction Angstrom exponent EAE (left) and the retrieved lidar ratio LR (right). The legend displays the number of simultaneous measurement pairs, the number of points within a ±0.02 AOD interval, Pearson's correlation coefficient and slope of the linear fit (see also Table 1).

Filtering for homogeneous sky conditions increases the correlation coefficient of the pairs to 0.78. Statistics of these and the following comparisons plots are summarized in Table 1.

Aeronet vs V-Profile-AODs using fixed LR= 30 sr

Comparisons same as above (LR = 30 sr) were performed using the V-PROFILES retrievals. In Fig. 3 we compare the resulting AODs to the AERONET ones. In this case, a number of points, mostly corresponding to AOD>0.05 and large EAE values (small particles), are overestimated (linear-fit slope of about 2). Such behavior persists also in the Almucantar-screened AOD series (Fig. 3, right). As mentioned in Section 2, number of comparable points in this case is 197, and 60% of them fall within the Aeronet AOD ±0.02. Further statistics of this comparison are reported in Table 1.

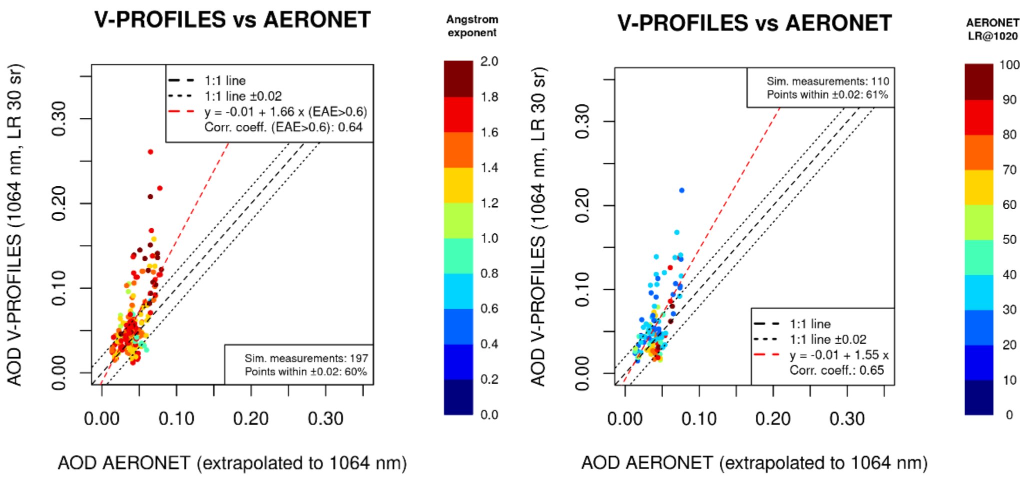

Figure 3. Scatterplot of AODs from V-PROFILES (using a LR = 30 sr) compared to AERONET L1.5 data (left) and Almucantar data (right). The colour scale indicates the extinction Angstrom exponent EAE (left) and the retrieved lidar ratio LR (right). The legend displays the number of simultaneous measurements, the number of points within a ±0.02 AOD interval, and Pearson's correlation coefficient and slope of the linear fit (e. g., Table 1).

Aeronet vs Alicenet-AODs using variable, backscatter-dependent LR

This comparison (Fig. 4) includes Alicenet AOD retrievals performed without an a-priori assumption of LR but using extinction to backscatter relationship derived from the Alicenet continental aerosol model (Dionisi et al., 2018). As mentioned, this model provides a backscatter-dependent lidar ratio, the average LR being LR=39 sr. Compared to the fixed LR cases in Fig. 2, the comparisons against L1.5 AERONET AODs (left plot) show a better agreement (83% of points within ±0.02 of the AERONET AOD, linear fit slope of 0.85). Still, some points with low EAE (coarse particles) remain underestimated, while some points with high EAE (fine particles) are overestimated. When addressing the filtered homogeneous sky Almucantar retrievals (Fig. 4 right), statistics improves slightly, but the number of comparisons reduces significantly, from 1310 down to 161 pairs.

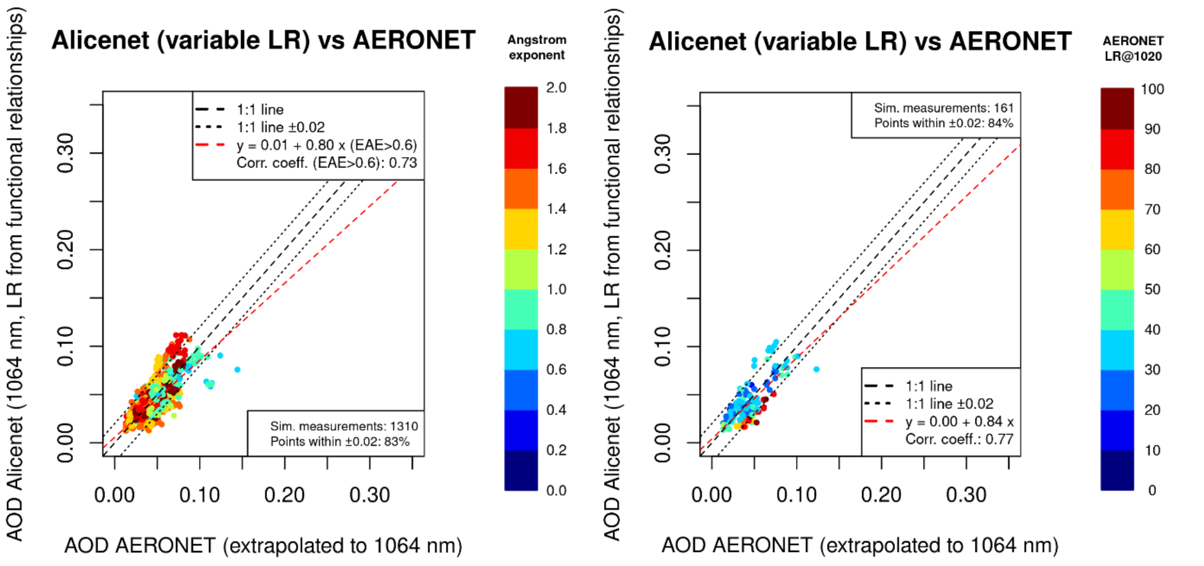

Figure 4. Scatter plot of 1064 nm AODs from Alicenet (using the Alicenet model's variable LR) compared to AERONET L1.5 data (left) and Almucantar data (right). The colour scale indicates the extinction Angstrom exponent EAE (left) and the retrieved lidar ratio LR (right). The legend displays the number of simultaneous measurements, the number of points within a ±0.02 AOD interval, and Pearson's correlation coefficient and slope of the linear fit (see also Table 1).

Aeronet vs Alicenet-AODs coinciding with the V-PROFILE series

The last comparison is made employing Alicenet profiles measured at the same moment and averaged along the same time as the V-PROFILES ones. As mentioned, this reduces the number of Alicenet profiles from 1310 (5-min averaged) down to 193 (1-h averaged) ones. Both retrievals (LR=30 and variable LR) are considered. The relevant results are reported in Fig. 5.

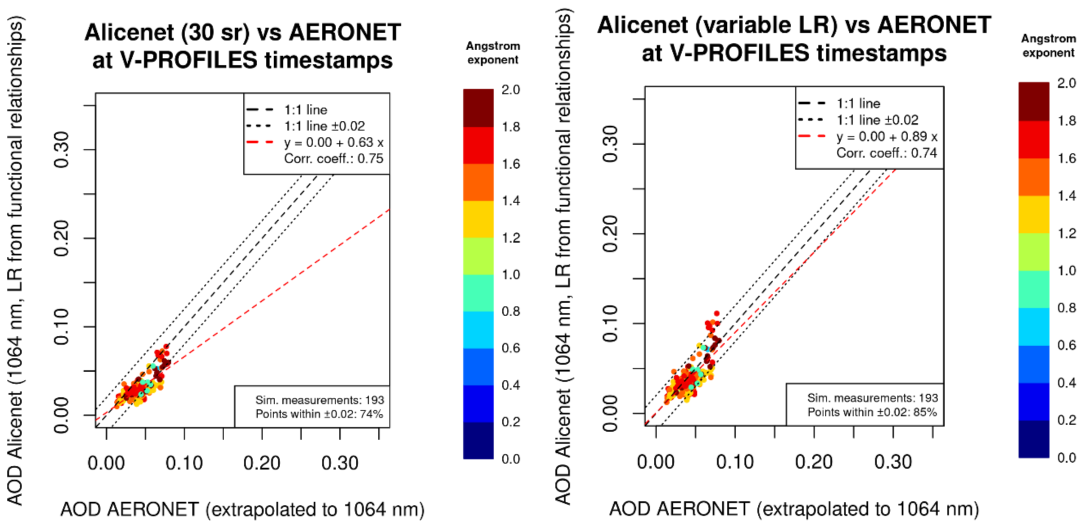

Figure 5. Scatter plot of AERONET L1.5 data compared to Alicenet 1064 nm AODs computed at the same time and with the same averaging period (1-h) as the V-PROFILES ones presented in Fig. 3. Retrievals made using LR=30 are shown in the left figure, while the ones made using the Alicenet variable LR are reported in the right-end figure. The colour scale indicates the extinction Angstrom exponent EAE.

Table 1. Statistics of the AOD comparisons as of Figs. 2, 3, 4 and 5.

Figure/Case	LR (sr)	Number of points	Pearson's Corr coeff	Slope (EAE>0.6)	% Points within 0.02	p-value
2 a Alicenet vs EAE	30	1310	0.74	0.56	71	<2.2e-16
2 b Alicenet vs LR	30	161	0.78	0.59	71	<2.2e-16
3 a Vprofiles vs EAE	30	197	0.64	1.66	60	<2.2e-16
3 b Vprofiles vs LR	30	110	0.65	1.55	61	2.8e-14
4 a Alicenet vs EAE	Model	1310	0.73	0.80	83	<2.2e-16
4 b Alicenet vs LR	Model	161	0.77	0.84	84	<2.2e-16
5 a Alicenet 1-h avg	30	193	0.75	0.63	74	<2.2e-16
5 b Alicenet 1-h avg	Model	193	0.74	0.89	85	<2.2e-16

Discussion

Comparisons addressed in Figs. 2-to-5, and summarized in Table 1, helped assessing the following points:

1) A significantly good Alicenet AOD retrieval (83-85% of points within ± 0.02 from the Aeronet AOD) was obtained by applying the forward Klett retrieval, with model-derived lidar ratio (average LR=39 sr) and night-time-evaluated calibration constants. Retrievals performed using a fixed LR=30 sr produced fair results (71-74% of points within ± 0.02 from the Aeronet AOD), with systematic underestimation of the AODs.
2) In the case of Alicenet, the AOD discrepancies were found to be generated by: a) the (hard-to-assess) presence of thin cloud/inhomogeneous aerosol layers within the two measurement fields-of-view, and b) a short (5-min) averaging time. Filtering-out of these cases (as done by the homogeneous sky Almucantar retrievals), and/or increasing the profiles averaging time were demonstrated to sharply increase the number of AOD retrievals within ± 0.02 from AERONET ones. Departure from this range is therefore likely caused by real AOD differences between the AERONET and the ALC optical paths.
3) Even employing a low lidar ratio (LR=30), a systematic overestimation of the ALC-derived AOD was observed in the V-PROFILE, "backward Klett", continuous calibration retrievals. Use of a more appropriate lidar ratio (LR=40 or LR=50 in the case of mineral dust) would lead to even higher values of the AODs. Reasons for such overestimation can include the backward, daytime Klett inversion, presence of low layers below the minimum extrapolation altitude, and unfiltered clouds in the backward Klett inversion. Some unexpected AOD peaks were also detected in clear sky conditions (e.g. Appendix 2) and would merit further investigation. The overestimation observed in this comparison could also explain the higher values of the Stromboli volcanic ash retrieved by V-PROFILE with respect to Alicenet.
4) Choice of the correct lidar ratio was confirmed to be fundamental to obtain a best retrieval of aerosol properties out of lidar profiles (e.g., Appendix 1). LR at 1064 nm can strongly vary from values of the order of 20 sr for haze, up to 40 sr for average continental aerosols and up to 50-100 sr for mineral dust and absorbing aerosols. These tests provided best results when employing a "continental aerosol" model characterized by an average LR=39 sr.

Recommendation: before moving to mass retrieval by either exploiting ALC extinction or backscatter profiles, all causes of the discrepancies described in this note should be taken into account in the E-Profile data processing chains.

References:

Dionisi, D., F. Barnaba, H. Diémoz, L. Di Liberto, and G. P. Gobbi, A multi-wavelength numerical model in support of quantitative retrievals of aerosol properties from automated lidar-ceilometers and test applications for AOT and PM10 estimation, Atmos. Meas. Tech., 11, 6013–6042, 2018.

Eck, T. F., B. N. Holben, J. S. Reid, O. Dubovik, A. Smirnov, N. T. O'Neill, I. Slutsker, and S. Kinne (1999), Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols, J. Geophys. Res., 104(D24), 31,333–31,349, doi:10.1029/1999JD900923.

Wiegner, M., and A. Geiss, Aerosol profiling with the Jenoptik ceilometer CHM15kx, Atmos. Meas. Tech., 5, 1953–1964, 2012.

Appendix 1

Some long series of Aeronet retrievals of the 1020nm lidar ratio (LR, level 1.5 inversions) over Europe and North Africa have been evaluated to understand their variability as a function of latitude and aerosol type. The series span from 53N (Hamburg, Germany) to 31N (Ouarzazate, Morocco). The sites were selected as representative of industrialized areas, large cities, coastal cities and north Africa coastal and desert areas. LR average (with standard deviation) and median values are reported in Table A1.1 together with location coordinates and length of data series.

With the exception of Ouarzazate, these statistics show no significant differences to characterize the 1020nm lidar ratio across Europe. As a matter of fact, lidar ratios stay mostly in the range 37-42 sr, confirming the results of the Alicenet aerosol model by Dionisi et al. (2018), this indicating LR=39 sr at 1064 nm as a good average for “continental” aerosols. LR mean values are somewhat higher in large cities, reach a minimum in the coastal site of Messina (likely affected by some marine particles), and maximize at locations affected by Saharan dust advections (median values of about 60 sr in the “dominant dusty” conditions of Ouarzazate), due to a known effect of LR increase in presence of non-spherical dust particles.

Table A1.1 long-term statistics of Aeronet “inverted” lidar ratios at six stations spanning Europe and North Africa.

Aeronet Station	LAT, LON	Years	#pts.	LR1020 (avg)	LR1020 (stdev)	LR1020 (mdn)
Hamburg	53.568N, 9.973E	2000-2019	2319	41.0	19.3	37.0
Ispra	45.803N, 8.627E	2001-2020	8027	38.9	14.9	36.7
Roma	41.840N, 12.647E	2001-2019	11759	40.9	13.9	39.1
Messina	38.197N, 15.567E	2005-2020	7628	37.0	12.4	35.5
Tunis	36.839N, 10.200E	2013-2020	7924	42.2	14.1	40.7
Ouarzazate	30.928N, 6.913W	2012-2015	5493	77.0	43.5	62.7

Appendix 2

To provide some examples of the daily analysis performed, two cases are presented in Fig. A2.1 (22/1/2020), and Fig. A2.2 (12/4/2020), respectively. These include some unexplained peak values in V-PROFILES AODs, possibly leading to the overestimates presented in Fig. 3 of the main text.

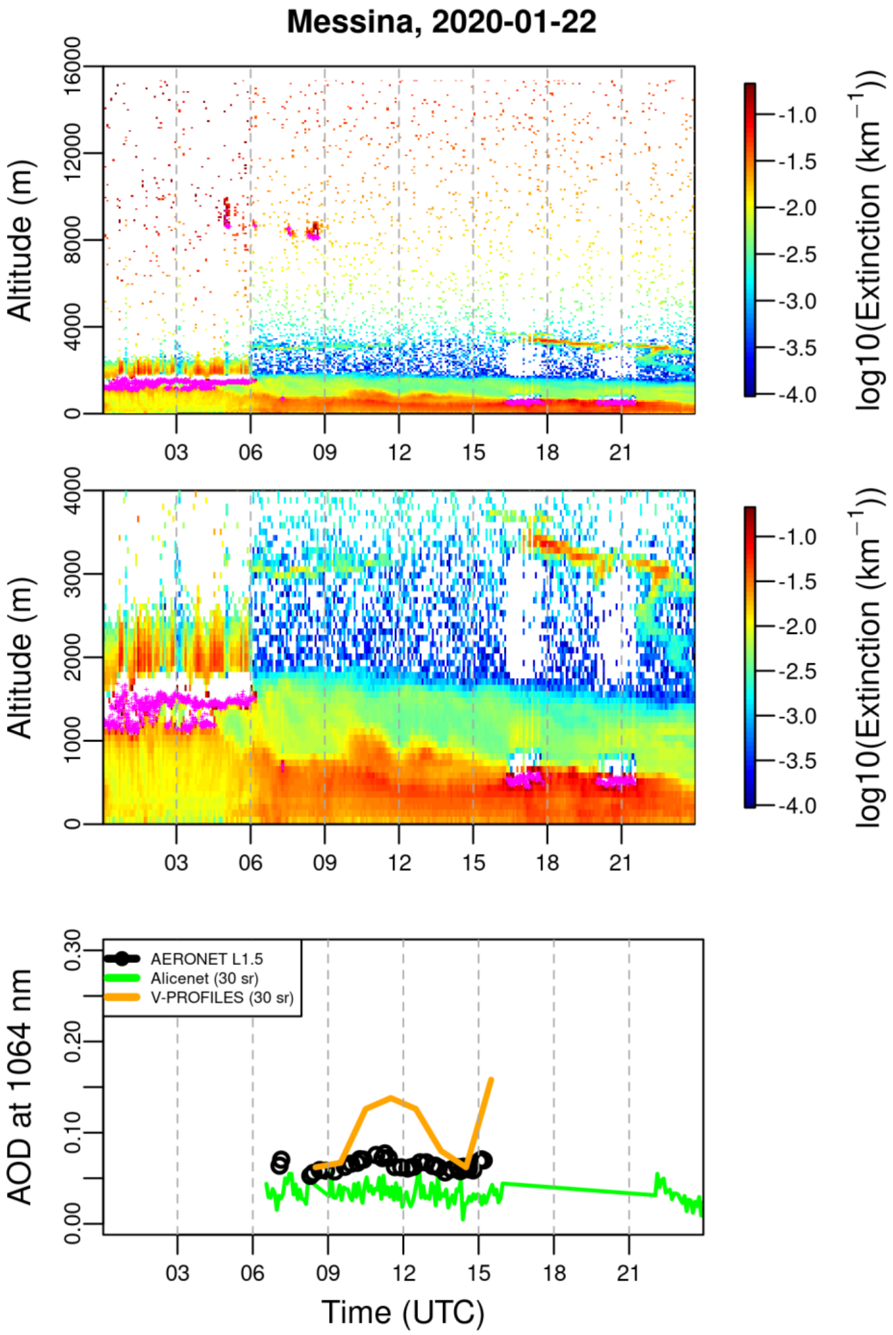

Figure A2.1. 1064 nm extinction coefficient retrieved by Alicenet on January 22, 2020 using LR = 30 sr along the whole range sounded by the ALC (upper panel) and zoomed over the lower 4000 m (central panel). The pink dots represent the bottom of the clouds as determined by the ALC firmware. White pixels identify the areas where the SNR drops below 20%. Lower panel: 1064 nm AOD as retrieved by

Alicenet (30 sr), V-PROFILES (30 sr) and AERONET.

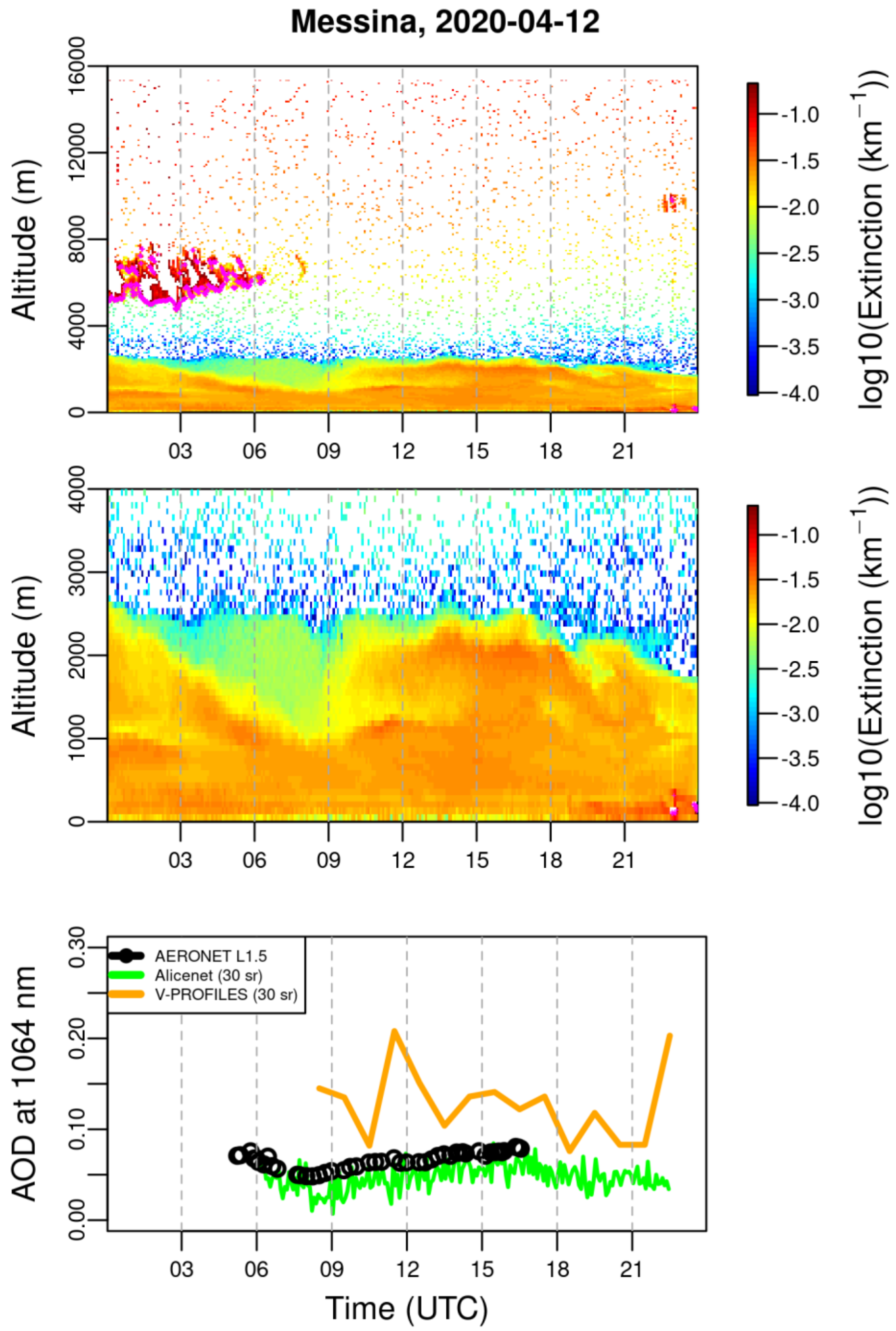

Figure A2.2. As in Fig. A2.1 but for April 12, 2020.