Intercomparison of aerosol measurements performed with multi-wavelength Raman lidars, automatic lidars and ceilometers

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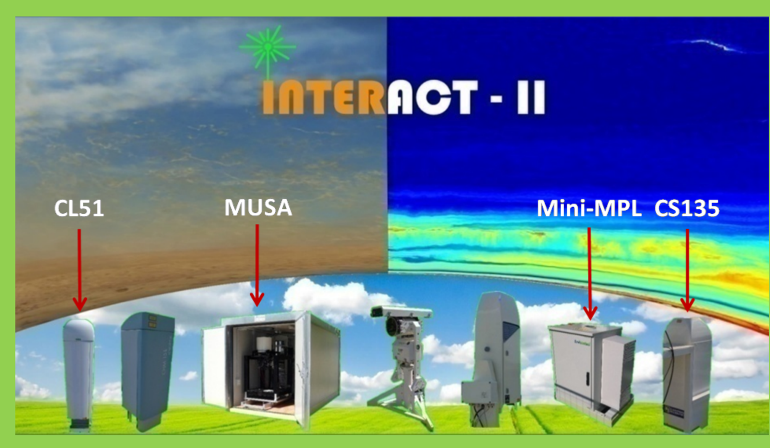
Motivation and scientific objectives

The study and monitoring of aerosol spatio-temporal distribution in troposphere is essential to improve our understanding of climate and air quality. For this purpose, global scale high resolution and continuous measurements of tropospheric aerosol properties are needed. Advanced multi-wavelength lidars are the best instruments to retrieve high resolution profiles of aerosol properties, but, because of their high complexity and cost, they are limited in number and most of them are operated not continuously, making the global coverage and continuity of their measurements not sufficient for climate and air quality studies. Therefore, there is a great interest for scientific community to understand to which extent commercial automatic lidars and ceilometers (ALCs), which are low cost, global coverage and continuously operating instruments, can provide reliable aerosol measurements and fill in the gaps of existing networks of advanced lidars, such as EARLINET (European Aerosol Research LIdar NETwork).

The INTERACT-II (INTERcomparison of Aerosol and Cloud Tracking) measurement campaign [1], carried out at CNR-IMAA Atmospheric Observatory (CIAO) in Tito Scalo, Potenza, Italy (40.60°N, 15.72°E, 760 m) from July to December 2016 within the activities of ACTRIS-2 (Aerosol Clouds Trace gases Research InfraStructure) H2020 research infrastructure project, aims to evaluate the potential of ALCs for tropospheric aerosol profiling, by comparing the measurements of these instruments with simultaneous and co-located measurements of advanced EARLINET multi-wavelength lidars operational at CIAO, considered as a reference.



Instruments at CIAO observatory during INTERACT-II

Involved instruments

- Two advanced multi-wavelength Raman lidars operational at CIAO: PEARL (Potenza EArlinet Raman Lidar) and MUSA (MUlti-wavelength System for Aerosol), which is a mobile EARLINET reference lidar.
- A Mini-Micro Pulse Lidar (mini-MPL) provided by Sigma Space Corporation/Envicontrol, which is an automatic system operating at 532 nm.
- Two ceilometers, a CL51 provided by VAISALA and a CS135 provided by Campbell Scientific, operating between 905 and 910 nm and continuously providing attenuated backscatter coefficient profiles.

Provider	Model	Transmitted wavelengths (nm)	Detected wavelengths (nm)	Products
CIAO	MUSA/ PEARL	355, 532, 1064	355, 532, 532_p, 532_c, 1064 (elastic backscattering) 387, 607 (Raman backscattering)	$RCS_{all\ wavelengths}$ $\alpha_{355,532}$ $\beta_{355,532,1064}$ δ_{532}
Sigma Space	Mini-MPL	532	532_p, 532_c	NRB, α, β, δ
Vaisala	CL51	910 ± 10	910 ± 10	attenuated backscatter
Campbell	CS135	912 ± 5	912 ± 5	attenuated backscatter

Specifications of the instruments involved in INTERACT-II: CIAO lidars provide range corrected signal (RCS) at all the detected wavelengths and the profiles of aerosol extinction coefficient at 355 and 532 nm and backscatter coefficient at 355, 532 and 1064 nm. CIAO lidars also detect the co- and cross-polarized components of the elastically backscattered radiation at 532 nm, in order to measure the aerosol linear depolarization ratio at that wavelength. Mini-MPL provides continuous measurements of normalized relative backscatter (NRB), proportional to RCS, and profiles of aerosol extinction coefficient, backscattering coefficient and linear depolarization ratio.

Methodology

Mini-MPL & Ceilometers vs LIDAR

✓ Lidar measurements are processed using the EARLINET Single Calculus Chain (SCC) [2,3].

✓ All the time series considered in this study refer to night time clear sky measurements.

✓ Profiles from all the instruments are compared over a vertical resolution of 60 meters and an integration time ranging from 1 to 2 hours, depending on the observed atmospheric scenario. All the profiles are cut in lower part of the atmosphere, typically below 1.2 km above sea level (a.s.l.), so as the reference lidar profiles are in the region with the full overlap between the telescope field of view and the laser beam.

Mini-MPL vs LIDAR

✓ NRBs from Mini-MPL are normalized over the equivalent lidar RCSs at 532 nm in an aerosol free altitude range of 1.2 km, starting from a variable altitude between 6 and 8 km a.s.l. (molecular calibration). For both reference lidars and Mini-MPL, total signals at 532 nm are calculated by combining the signals of respective co- and cross-polarized channels, based on the different polarization setup of the systems [4,5].

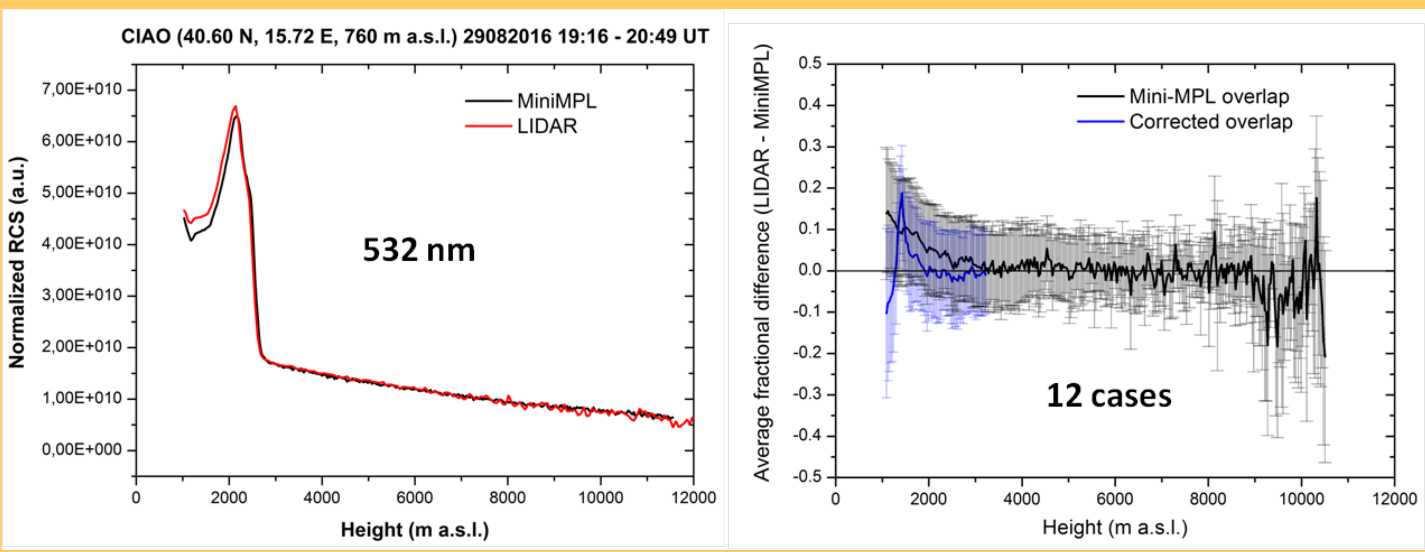
Ceilometers vs LIDAR

✓ Ceilometer attenuated backscatter profiles are normalized over the equivalent lidar profiles in an altitude range of 600 m below 3 km a.s.l. To compare the profiles at 910-912 and 1064 nm, obtained from ceilometers and lidars respectively, the spectral dependency of the attenuated backscatter is considered, using the 1064/532 nm backscatter-related Ångstrom exponent retrieved from lidar data processing. This is assumed the best approximation of the 1064/910-912 nm backscatter-related Ångstrom exponent.

✓ Ceilometer attenuated backscatter profiles are corrected for water vapor absorption, estimated using the Fu-Liou-Gu (FLG) radiative transfer model [6, 7] and, as input of the model, the data of collocated GRUAN (GCOS Research Upper-Air Network) radiosounding or RAOB (The Universal RAwinsonde Observation program) radiosoundings from Brindisi station (40.63N, 17.94E, 15 m), about 150 km East of CIAO station.

Results: Mini-MPL vs LIDAR

Left: *comparison between RCSs provided by lidar (red) and mini-MPL (black) on 29 August 2016 in the time interval from 19:16 to 20:49 UT. The Mini-MPL profile is normalized over the lidar profile.* ***Right:*** *the black line is the profile of average percentage differences between lidar and mini-MPL values of RCS measured in 12 simultaneous observations during the campaign. The vertical bars are the standard deviations of these differences. The blue line is the same as the black one obtained by applying an additional overlap correction to the MiniMPL, estimated using the data of the cleanest measurement session during the campaign.*



➢ The Mini-MPL underestimates the lidar at lower altitudes, up to 2 km, with differences increasing towards the ground level and less than 15% probably due to a not optimal overlap correction for Mini-MPL, which requires a deeper investigation. At higher altitudes, there is a good agreement between the Mini-MPL and lidars throughout the troposphere, with differences < 5% .

➢The additional overlap correction reduces average differences in the range 1.5 -3km, with values less than 3% from 1.8 km, improving mini-MPL performance.

➢The standard deviation of average percentage differences in the normalization region ranges within 10% and the stability of the lidar normalization (i.e.molecular calibration) during the campaign is within ±29%.

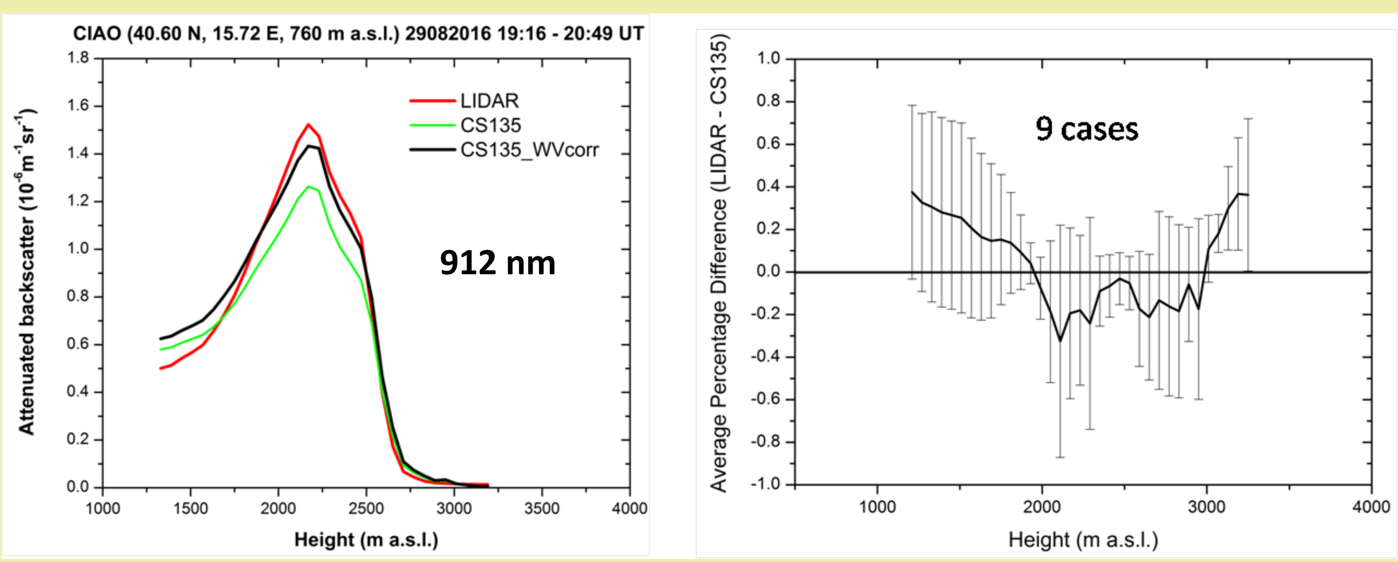
Mini-MPL:

- **Very good potential for aerosol profiling through the whole troposphere**
- **Good stability and accuracy of molecular calibration during the campaign**
- **Possible improvement in the evaluation of overlap correction function by the manufacturer**

Results: Ceilometers vs LIDAR

CS135 vs LIDAR

Left: *comparison between attenuated backscatter profiles provided by lidar (red) and CS135 (black) on 29 August 2016 in the time interval from 19:16 to 20:49 UT. The CS135 profile is corrected for water vapor (WV) absorption and normalized over the lidar profile in an altitude range below 3 km. The green line is the CS135 profile not corrected for WV absorption.* ***Right:*** *profile of average percentage differences between lidar and CS135 values of attenuated backscatter, with their standard deviations (vertical bars). The profile refers to only 9 simultaneous observations during the campaign.*



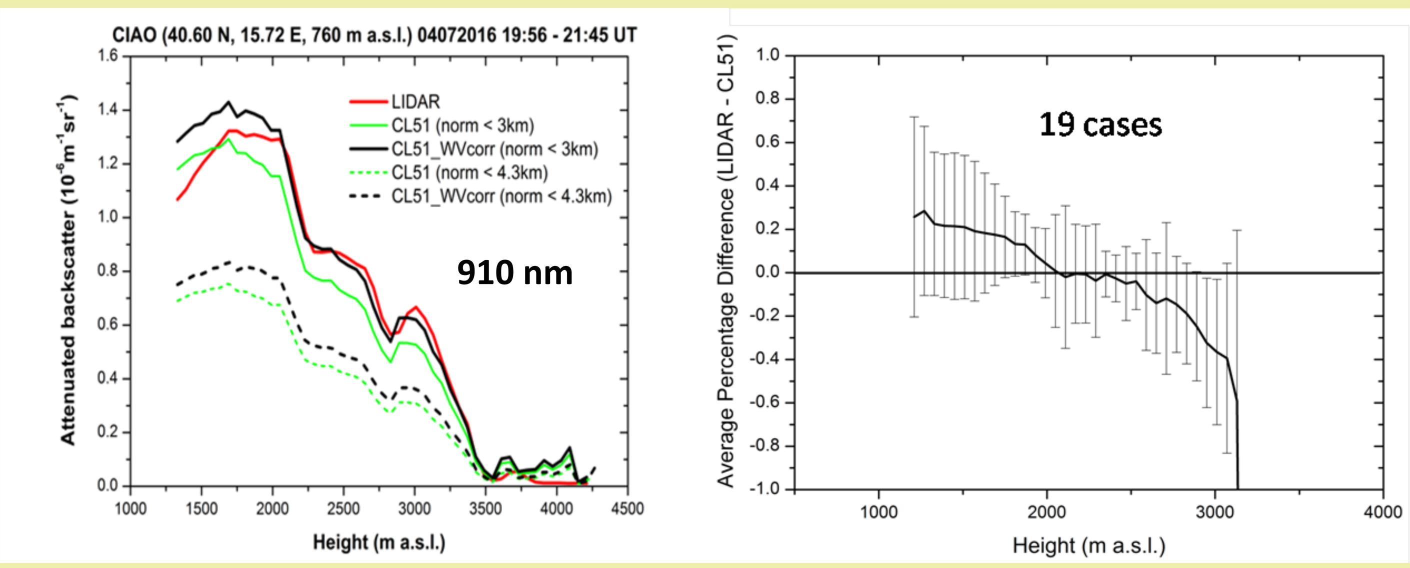
➢ Differences between the CS135 and reference lidars are generally within 20-30% up to about 3km, increasing towards the ground level, probably due to overlap correction issues. At higher altitudes, above 3 km, differences increase because of the low ceilometer signal to noise ratio (SNR).

➢ In the vertical region between 2 and 3 km, where normalization is generally operated, the variability of average differences typically ranges within 50%, while the normalization stability during the campaign is within ±47%.

CS135:

- **Good potential for aerosol profiling only in the planetary boundary layer (PBL)**
- **Very low SNR in the free troposphere (FT), which makes molecular calibration impossible; the mid term (6 months) stability of the normalization over the lidar in PBL is challenging**
- **Data collection affected by a technical problem, which caused the loss of data (only 9 comparisons with lidar available during the campaign)**

CL51 vs LIDAR



Left: *comparison between attenuated backscatter profiles provided by lidar (red) and CL51 (black) on 4 July in the time interval from 19:56 to 21:45 UT. The CL51 profile is corrected for WV absorption and normalized over the lidar profile in an altitude range below 3 km. The green line is the CL51 profile not corrected for WV absorption. Dash lines are the corresponding CL51 profiles obtained with an higher normalization range, below 4.3 km.* ***Right****: profile of average percentage differences between lidar and CL51 values of attenuated backscatter, with their standard deviations (vertical bars). The profile refers to 19 simultaneous observations during the campaign.*

➢ The low SNR of the CL51 above 3 km can make the normalization over the lidar in the FT(i.e.molecular calibration) quite inaccurate, resulting in a bias of the retrieved attenuated backscatter profile: only the normalization over reference lidar profiles below 3 km allowed a reliable estimation of the CL51 attenuated backscatter profiles.

➢ Differences between the CL51 and reference lidars are less than 20% up to about 3 km, increasing towards the ground level, probably due to overlap correction issues. At higher altitudes, differences increase because of the low ceilometer SNR.

➢ In the vertical region between 2 and 3 km, where normalization is generally performed, the variability of average differences typically ranges within 40%, while the normalization stability during the campaign is within ±46%.

CL51:

- **Good potential for aerosol profiling in PBL, with the ability to detect thin aerosol layers in FT**
- **Molecular calibration is possible over an integration time of 1-2 hours, but it may be quite inaccurate because of too low SNR; the performance of appropriate dark measurements and subtraction as well as of integration time longer than 1-2 hours to enable the molecular calibration for 905-912 nm ceilometers is currently under investigation through analysis of the database collected during the CeiLinEX Campaign [8]**
- **The mid term stability of the normalization over the reference lidar in PBL is challenging**

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