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The INFN Raman LIDAR aerosol measurements at CTAO North and its future deployment at CTAO South

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Abstract. For the pre-production phase of Cherenkov Telescope Array Observatory (CTAO), the INFN Raman Lidar (IRL) has collected vertical profiles of aerosol optical properties in the UV region at Roque de los Muchachos Observatory (ORM) up to December 2022, in automatic and unattended mode. A survey of the atmospheric aerosol climatology will be presented together with an overview of case studies. The IRL is currently at our laboratory in L'Aquila (Italy): an overview about the status of the upgrades (already implemented and ongoing) to improve its performances before its deployment at the CTAO South site, is also presented.

1. General Overview.

The IRL is a compact and portable system and was chosen as part of the CTAO for the ORM site characterization of the aerosol attenuation profiles in the UV region with the goal of making a first survey of the aerosol and water vapor contents/local climatology. The IRL is based on a Nd:YAG pulsed laser emitting at 355nm with a repetition rate of 100Hz and a pulse duration of 7ns. It has been updated and tested in L'Aquila before been moved to ORM in October 2018 [1][2]. The IRL has collected vertical profiles of aerosol optical properties and water vapor two times a day, at sunrise and sunset, in automatic and unattended mode up to December 2022. Since its installation the RL has performed over one thousand 15-minutes measurements sessions. No measurements have been done in case of precipitation, fog or for technical problems (computer or network failures etc.). During data analysis, part of the measurements has been discarded (bad alignment, dirty exit window, low level clouds etc.). We suffered some major problems mainly due to the lack of proper on-site services caused by the COVID-19 outbreak. Because of that, from 2021 the Raman channels are offline.

The Canary Islands are generally characterised by stable atmospheric conditions and at the ORM site, located at an altitude of over 2000 metres above sea level, clear sky conditions are common. The relatively clean and dry atmosphere is one of the reasons why ORM was chosen for the CTAO (and other astronomical instrumentation), however, the Canary Islands are also exposed

to the presence of strong aerosol loads during frequent Saharan dust (SD) events [3], the so-called 'Calima'.
In Figure 1, there is the aerosol optical parameter's profiles of a SD event occurred during summer with the corresponding satellite image [4] underlining the large-scale extension of these events that often cross the Mediterranean Sea and can reach the American side of the Atlantic Ocean, with the back trajectory [5] able to provide further confirmation also on the vertical extent of the event. The IRL, when in good shape and within limits [1], can measure reliable optical properties

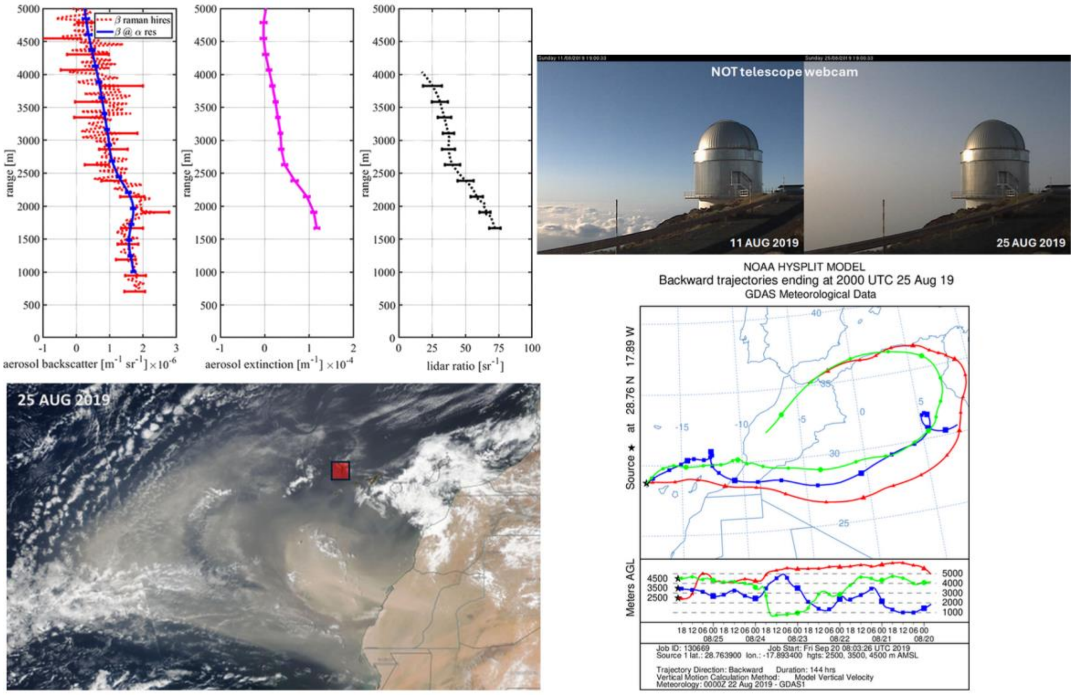

Figure 1. On the upper left panel, the profiles of the aerosol's optical parameters of summertime SD event (25 August 2019) retrieved with the Raman technique. On the upper right panel, the visual difference between clear sky condition and a sky with SD, the latter taken on same day of data displayed on the left (courtesy of the Nordic Optical Telescope (NOT) telescope webcam at ORM). On the bottom left panel, the satellite image and on the bottom right the back trajectory.

in the troposphere as can be seen in this Figure where on the left upper panel, the red line is the aerosol backscatter profile with 30m vertical resolution, while the blue line it is scaled to the same resolution of the aerosol extinction and is used to calculate the lidar ratio (S) profile [6], which is the aerosol extinction to aerosol backscatter ratio, a parameter that is fundamental for aerosol classification; the colour scheme significance for this panel holds also in Figure 2 for the 14 Feb 2020 case.

2. Aerosol optical parameters measurements.

Time series of about one thousand of aerosol backscatter profiles in Figure 2 (left panels) showed a lower aerosol content in winter and spring, as expected for a mountain site. However, Saharan dust events are often present during summer and early autumn. During winter and spring, SD events appear more sporadic, but not absent, and with different vertical morphology as will be also discussed below. There is also a lack of data of more than one month for the volcano eruption in 2021 due to the ashes in the exit window. Moreover, after some strong SD events, the lidar output window may be also so dirty that no measurements can be taken until proper cleaning is carried out.

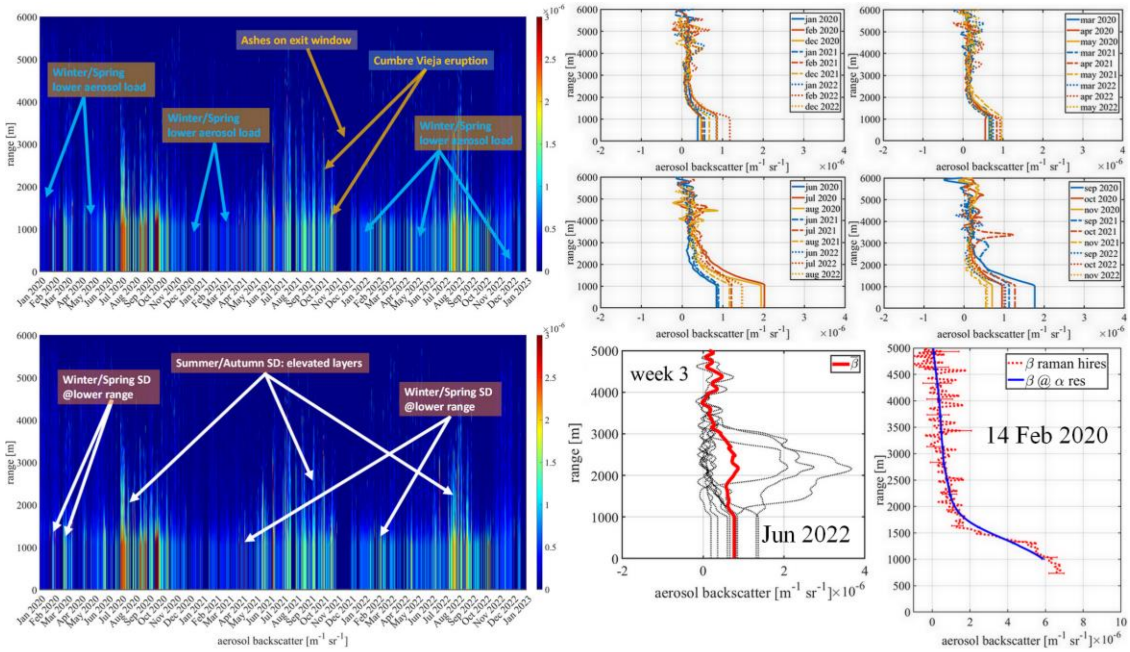

Figure 2. On the left, two panels of the three years' time series of the aerosol backscatter profiles with highlighted different aerosol characteristics. The maximum value of the aerosol backscatter scale has been limited to visual enhance the main characteristics of the profiles. On the upper right, four panels (one for each season) with monthly averages. No averages for Nov 2021 due to the few data available because the volcano ashes presence on the exit window of the IRL. On the bottom right, two panels with a couple of examples for SD events, one in summer (Jun 2022) and one in winter (14 Feb 2020).

From Figure 2 (upper right, four panels) one can notice the typical low aerosol load (generally <1 10^{-6} m^{-1} sr^{-1} at 1000m range) during the DJF and MAM months: these values could be considered as typical background conditions. The relatively few Saharan dust cases that are recorded during these months, did not show the presence of an elevated dust layer (see 14 Feb 2020 case, Figure 2 bottom right panel, at right). In those months, the aerosols are generally well confined in the first 1500-2000m a.g.l. in almost any condition.

Regarding the JJA months, in Figure 2 we can observe a different and more pronounced impact of the SD cases on average aerosol backscatter profiles. In fact, those profiles are characterized by the presence of SD in more elevated layers and by a higher backscatter value at 1000m a.g.l as in the left side of bottom right panel with the aerosol backscatter data for the third week of June 2022 (red line is the average). Strong SD events are also present in the SON profiles, especially in September together with the volcanic aerosol's signature in September/October 21. The Cumbre Vieja eruption began on 19 September 2021 [7], resulting in severe suffering for the population and the interruption of almost all scientific activities at the ORM. We were able to collect data since its onset and to produce short reports on the preliminary analysis of the profiles in cooperation with the State Meteorological Agency of Spain (AEMET). As can be seen in Figure 3, the volcanic emissions were not always recorded in the aerosol backscatter profile primary because the plume's trajectory was not always directed towards the IRL i.e. in the northward quadrant from the volcano position (as happened on 01 October), which is confirmed by the

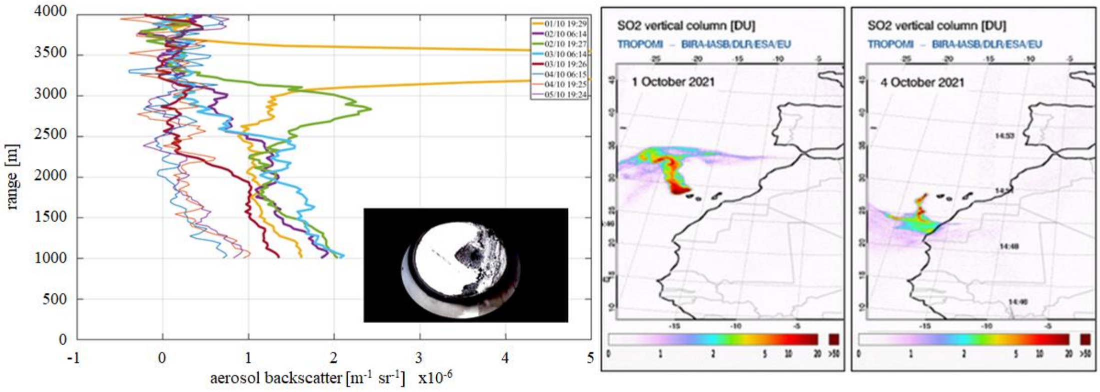

Figure 3. On the left panel some the aerosol backscatter profiles taken during the volcanic eruption. Thin line for background aerosol, thick lines for volcano aerosol. A photo of the lidar exit window covered with the volcano's ashes is also inserted. On the right panel the TROPOMI satellite data on the SO_2 column.

TROPOMI SO_2 satellite observations [8] in the right panel. Ashes on the lidar window stopped the data flow from November 2021 to mid-December 2021.

At the ORM there is a sun photometer, part of the AERONET network [9], whose data we used in various ways, e.g. to identify SD cases. We also explored the possibility to constrain the aerosol optical parameter retrieval of the IRL with both the sun photometer data, aerosol optical depth (AOD) and angstrom exponent (AE), and to the degree of stratification of the aerosol layer in the not complete overlap region. The latter has been performed by finding optimal value of the optical

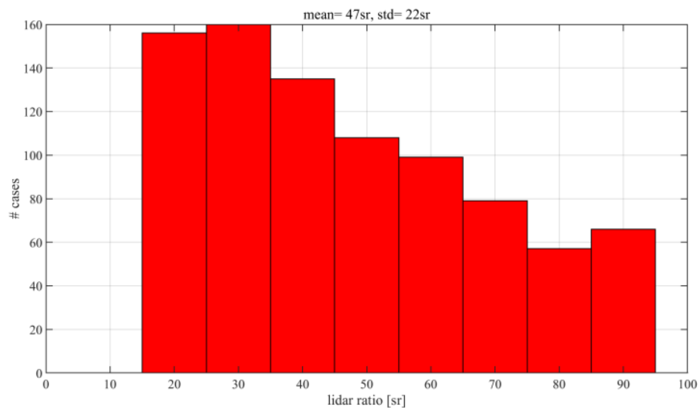

Figure 4. Lidar ratio distribution found with the optimization procedure.

parameters at ground assuming a constant slope from the start of the complete overlap. This has been done to enhance the IRL data retrieval, especially since the Raman channels went offline. This method allows to estimate S, which is a parameter required by the algorithm to retrieve the aerosol backscatter profile from the elastic signal. The lidar ratio distribution found applying this method (Figure 4) is compatible with the aerosol's characteristics of the site i.e. from a significative presence of marine aerosols (lower S) to SD and other aerosol mixture with a higher S.

In Figure 5 can be seen the histogram of the difference between the AOD from aerosol extinction profile (nitrogen Raman channel, 2020 data) with stratification optimization, which represent the reference value, and in the left panel, the AOD estimated from the lidar ratio and the aerosols backscatter profile from the elastic inversion in the blind case (i.e. with S fixed to 50sr and fixed stratification in all the retrievals). In the right panel, the lidar ratio and the aerosols backscatter profile are retrieved applying the sun-photometer data constraints and the stratification optimization to the elastic inversion.

Just from a visual inspection, it is quite evident that an improvement is achieved in the latter case. Outliers, with huge impact on the statistic, have been found mainly in the latter case with

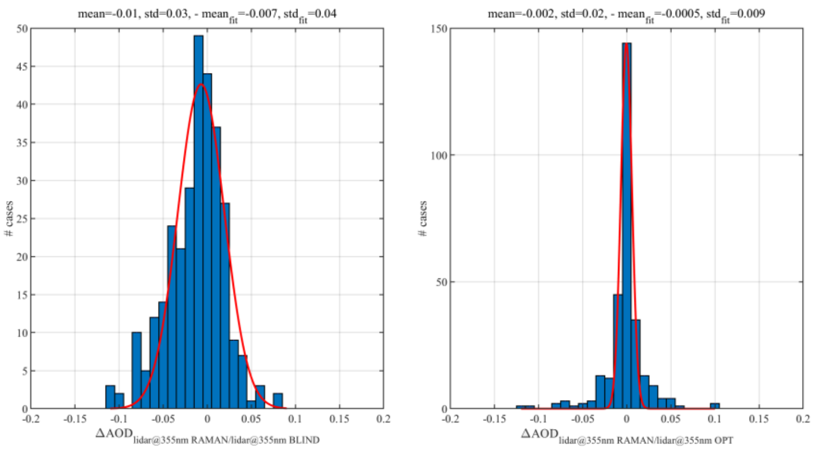

Figure 5. Histograms of the differences between the reference case (AOD from Raman data with optimized stratification) and AOD estimated from the elastic inversion (blind case on the left, optimized case on the right).

different methods all of which indicates the negative deviations <-0.1 as outliers. We choose the outliers finder method that removes the least of data point (up to 9 data over a 304 total) which is the one that marks as outliers the elements more than three standard deviations from the mean. As a result, both the mean of the difference and the standard deviation are significatively lowered, especially in the gaussian fit of those data, reinforcing the possibility that applying this method had a positive effect on data reliability. It should be noted that this method, only briefed described here, is still under testing and the results should be considered preliminary [10].

3. Status and future deployment at CTAO-South.

At the beginning of 2024, the IRL was shipped back to our laboratory in L'Aquila, Italy, to be equipped to be fully operational for its destination at the CTAO South site (Paranal Desert, Chile).

For this reason, a new container with e.g. outlets for the laser beam and quartz window was specially prepared both for transport by sea and to serve as a laboratory once at destination. In addition, several technical improvements will be applied to the lidar system, such as a motorised cover to have a cleaner output window, a new laser beam output to reduce stray light, and the modification of the telescope/receiver coupling, from mirrors to an optical fiber bundle, to improve optical stability, performances and to lower systematic uncertainties in the data produced, including by significantly reducing the region of incomplete overlap. The optical fiber consists in an input end bundle with a NA 0.22, which divides in three output ends, with homogenous randomization of fibers between input and output bundles and is designed also to avoid fluorescence. Before being shipped to the final site, various tests and quality checks will also be carried out as was done before the IRL was installed at ORM.

4. Conclusions.

The IRL collected about one thousand vertical profiles of the aerosol optical properties in automatic and unattended mode. Water vapor profiles have been also recorded but their analysis are outside the scope of this work. The IRL has been proven robust and reliable, although the forced lack of services has partially reduced its potential. Of course, we want a fully operationally Raman Lidar, able to get independent aerosol optical properties from as near as possible to the ground, but nevertheless possibility to exploit the sun-photometer data and the stratification optimization, enabled to cover with reliable and homogeneous aerosol backscatter profiles a large period with the Raman channels offline. The data analysis permitted a preliminary study of the aerosol optical properties seasonal cycle which appears to be characterized by an overlay between the SD outbreak events and the local troposphere with a lower aerosol load of marine origin, the latter a more common feature for a mountain site in an island. We have been able to record profiles of aerosol backscatter during the Cumbre Vieja eruption and to observe how, even if we are located quite near the source, not always we were able to measure the volcanic plume.

The IRL now is back in our laboratory in L'Aquila (Italy) to perform technical upgrades and tests before going to the CTAO south site in Chile.

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