WP20–JRA1: Lidar and sunphotometer – Improved instruments, integrated observations and combined algorithms

Deliverable D20.5: Report on the implementation and test of optimized techniques for daytime Raman lidar observations

Objectives

Task 1 of WP20 aims at the improvement of daytime capabilities of lidar instruments to profile aerosol extinction. A few lidar techniques have been developed to improve Raman lidar daytime capabilities. These solutions have been reviewed in the deliverable WP20.1. The task activity from month 12 to 36 is focused on the assessment of the performances of the existing instruments for the daytime detection of the Pure Rotational Raman Spectrum (PRRS) to retrieve aerosol extinction profiles.

Theory: retrieval of extinction coefficient

Aerosol extinction profiles are quite frequently measured with elastic backscatter lidars using Fernald or Klett inversion techniques in which the lidar ratio and the extinction at a reference altitude have to be assumed. By using the nitrogen rotational-vibrational Raman signal, the retrieval of the aerosol extinction coefficient is possible with the single assumption about the wavelength dependence of the aerosol extinction.

The aerosol extinction can be obtained from the measurements of the PRRS lidar signal without any assumption about the aerosol and atmospheric optical properties because of the spectral closeness of the PRRS and the laser excitation line. The main obstacle for aerosol measurements, the temperature dependence of the PRRS, can be solved by using the sum of the lidar returns from O and S PRRS branches which is practically independent of temperature.

The aerosol extinction profile can be retrieved from the PRRS according to the following equation:

$$\alpha_a(z) = -\frac{1}{2} \frac{d}{dz} \left[ \ln \frac{S_R(z)}{S_m(z)} \right]$$

where $S_m(z)$ is the molecular signal (calculated for example from the US standard atmosphere model, initialized with the temperature and pressure values measured at the lidar site), and $S_R(z)$ is the sum of the signals from the low and high quantum numbers’ spectral regions (SJL and SJH) selected for the detection of PRRS. It can easily be shown by direct calculations that $S_R(z)$ is practically temperature independent for suitably selected SJL and SJH.

Comparison of the different configurations for the retrieval of the aerosol extinction coefficient using rotational Raman lidar: Optical ray-tracing simulations

In this report, five configurations (CFG) for the receiver of a lidar system for detecting the PRRS also in daytime conditions are compared by means of numerical simulations. The CFGs are mainly differentiated by the design of the spectral selection unit implemented in the receiver of each lidar system that is respectively based on:
1. narrow-bandwidth filters plus Razor-edge filters, the latter used to suppress the elastic straylight, hereinafter “R”, as proposed by Reichardt et al., 2012;

2. narrow-bandwidth filters plus Razor-edge filters, like for R configuration, but using a simplified scheme, hereinafter named “M”, as proposed by Wandinger et al. (2012);

3. a grating spectrometer, hereinafter named “GS1”;

4. a double-grating spectrometer filtering the backscattered radiation in a sequential way, hereinafter named “GS2”;

5. a hybrid solution using a grating spectrometer followed by a Razor-edge filter, hereinafter named “GS+R”, designed as an intermediate configuration between filter- and grating-based configurations.

For the configuration based on the use of grating spectrometers, 5th-order gratings with 800 lines per mm have been used. The use of CFG1-4 is largely documented in literature (Reichardt et al., 2012; Serikov et al., 2010; Wandinger et al., 2012). The simulations involve only the part of the lidar receivers devoted to the detection of the PRRS; telescopes and all the optics located before the entrance pupil of each RRL channel have not been considered. Therefore, the reported results need to be re-considered in terms of the total optical efficiency of a lidar system, according to its own specific design, especially in the near and close range.

The total power is calculated as the integral over the detector area of the incoherent irradiance collected by the detector in the receiving channels. Detectors are assumed to be suitably designed, or at least oversized, to allow the detection of the backscattered radiation beam going through the telescope. Detectors are assumed to be homogenous over their whole sensitive surface.

Three types of sources have been used in the simulation:

1. a monochromatic source emitting a power of 1 W at each wavelength of the PRRS, simulated using an IDL routine. A ZPL macro for the different CFGs implemented in ZEMAX has been used to calculate the system optical efficiencies for each line (wavelength) of the PRRS;

2. a black-body spectrum source (T=5000 K) emitting a power of 1 W and restricted to the region 0.351 - 0.358 microns, used to simulate the solar background;

3. a monochromatic source emitting a power of 1 W at the laser wavelength ($\lambda_L=0.354852$ micron) to simulate the elastic scattering.

In the following plots, the results of the simulations are reported.

Figure 1: Comparison of the optical efficiencies (OE) with respect to the background radiation and the elastic aerosol backscattered radiation collected by each lidar receiver for the five configurations described in the text.
Figure 1 shows the comparison of the optical efficiencies (OE) with respect to the background radiation and the elastic aerosol backscattered radiation collected by each lidar receiver for the five configurations described above. Hereinafter, the five CFGs are reported in the text and the plots as R, M, GS1, GS2 and GS+R, according to the order described above. The comparison shows that the best performances, both for the background and the level of cross-talk suppression, are obtained with the GS2, GS+R and R CFGs, in the listed order. In terms of background, similar performances can be obtained among the different CFGs, except for GS2 that shows a better noise suppression. In terms of cross-talk suppression, GS2 shows a suppression of elastic aerosol scattering of up to $10^6$, which is about two orders of magnitude better than R and GS+R, and more than three orders of magnitude better than M and GS1.

In Figure 2, optical efficiencies (OE) of the considered lidar CFGs for each line of the PRRS are reported. OE has been obtained from ZEMAX non-sequential ray-tracing simulation. Simulations are based on the tracing of 5000 rays for each of the 64 simulated lines of the PRRS (320000 rays in total per simulation). In the left panel, OE for the channels of R and M are reported. These two CFGs are based on the detection of either the parallel (channel M1 and R1) or the cross-polarized component (channel M2 and R2) of the PRRS (Reichardt et al., 2012), therefore the OE for both channels are reported. The results shown in the next section for M and R configurations make use of the sum of lines of the S branch with low and high quantum numbers $J$, according to the depolarization of the PRRS. Similarly, contamination from elastic aerosol scattering has been calculated using the aerosol depolarization from the analysis of the true reference scenario. The polarizing beam splitter cube has been assumed to be ideal. In the right panel of Figure 2, OE for GS1, GS2 and GS+R are reported. These are all the CFGs based on the use of at least one grating spectrometer for the spectral selection of the PRRS. OE for all the CFGs are used in the following section where an assessment of the theoretical performances of the different CFGs in the retrieval of $\alpha$ during night-time and daytime conditions is discussed.

**Blind test**

To show the performances of the investigated lidar CFGs, a blind test has been carried out. The five CFGs have been used to calculate the night-time and daytime aerosol extinction profile starting from a known scenario. The atmospheric scenario used as the reference profile is represented by one of the night-time measurements with MUSA lidar at CNR-IMAA Atmospheric Observatory – CIAO (15.72E, 40.60N, 760 m a.s.l., Potenza, Italy). In Figure 3, the time series of the range-corrected signal at 1064 nm measured on 31 May 2013 is shown along with the corresponding “3+2”analysis (including linear particle depolarization ratio) performed in the time period between 23:32 and 00:39 UTC. In Figure 4, the 7-day backward trajectory analysis from the FlexPART model for both aerosol layers observed by MUSA at around 2 km a.s.l. (Figure 4a) and between 3 and 5 km a.s.l. (Figure 4b) is presented. The two layers...
originate from different regions and they are compatible with continental and mixed continental/mineral dust aerosol, respectively.

Figure 3: Left panel, time series of the range-corrected signal at 1064 nm measured on 31 May 2013 with MUSA lidar at CNR-IMAA Atmospheric Observatory (15.72E, 40.60N, 760 m a.s.l., Potenza, Italy); right panel, “3+2” analysis (including linear particle depolarization ratio) performed in the time period between 23:32 and 00:39 UTC on the same day.

Figure 4: 7-day backward trajectory analysis from the FlexPART model for both aerosol layers observed by MUSA at around 2 km a.s.l. (panel a) and between 3 and 5 km a.s.l. (panel b) is presented.

PPRS dependence on temperature (i.e., height) has been simulated using a temperature profile from a standard atmosphere calibrated at the ground level using CIAO PTU surface measurements. Simulation of daytime measurement conditions has been obtained by adding the solar background to the simulated signals according to the following equation:

\[ N_0 = \eta_0 \eta_a \frac{\lambda R \Delta t}{hc} \frac{AfW \Delta \lambda}{2\pi} \left( \frac{\theta}{2} \right)^2, \]
where \( N_0 \) is the number of background photons, \( \lambda \) is the received wavelength, \( A \) is the area of the receiver, \( f \) is the pulse repetition frequency, \( \eta_0 \) and \( \eta_q \) are the optical and quantum efficiencies of the receiver, respectively, \( R \) is the vertical resolution, \( t \) is the integration time, \( h \) is Planck’s constant and \( c \) is the speed of light, \( W \) is the zenith sky spectral radiance, \( \Delta \lambda \) is the receiver bandwidth and \( \theta \) is the receiver field of view.

Assuming a photon-counting mode of detection, RRL signals are obtained by summing the counts detected within the time bin \( [t, t+\tau] \) after the laser shot for each individual line of PRRS of nitrogen written as follows:

\[
n_i(r) = \frac{W_i f \pi D^2}{4 r^2 h v_0} KG(r) \beta_i(r) \frac{c r}{2} \exp \left\{ -\int_0^r \left( \alpha(v, x) + \alpha(v, x) \right) dx \right\}.
\]

Here \( \beta_i \) is the backscatter coefficient for each PRRS line, \( r = ct/2 \) is the distance from the lidar to the probe volume; \( W_i \) is the laser pulse energy; \( D \) is the diameter of the receiving telescope’s clear aperture; \( G(r) \) is the lidar overlap function; \( K \) is the total throughput of the transmitter-receiver-detector chain; \( \alpha(v, x) \) represents the atmospheric extinction at distance \( x \) for frequency \( v \). Finally, the spurious contribution to the RRL signals due to the elastic aerosol backscattering is calculated using the single-scattering lidar equation (Measures, 1984).

In Figure 5, the comparison of lidar signal profiles obtained from the simulated signals for the different lidar CFGs is reported. In Figure 5a, lidar signal profiles retrieved assuming the absence of elastic aerosol scattering and solar background are shown; in Figure 5b, lidar signal profiles obtained considering also the elastic aerosol scattering are shown; finally, in Figure 5c, lidar signal profiles during daytime (including elastic scattering and background) are shown. The vertical resolution of the profiles is 60 m and the temporal integration is one hour. All the signals have been generated for the far-range configuration of the telescope and using the OE simulated by ZEMAX. For all the CFGs, a telescope with a field of view (FOV) of 1 mrad and an effective entrance area of 0.5 m\(^2\) have been considered and a full overlap between the telescope and the laser source has been assumed. Moreover, Figure 5c also shows the effect of solar background on the signals for the different configurations.

In Figure 6, the results of the blind test are reported for the night-time and daytime measurement conditions, respectively. Figure 6 shows the comparison of the aerosol extinction coefficient (\( \alpha \)) profiles retrieved using the simulated signals for the different lidar CFGs against the true profile (MUSA). In detail, Figure 6a shows the profiles retrieved assuming the absence of cross-talks and noise; in Figure 6b, profiles in night-time conditions are reported; in Figure 6c, profiles in daytime conditions are reported; for the profiles reported in Figure 6a, b and c, the same resolution as the true scenario of 60 m (reported in the plot as “MUSA”) has been used, while in Figure 6d, the same profiles as in Figure 6c, but smoothed over 11 points, are shown.
Figure 5: Comparison of lidar signal profiles obtained from the simulated signals for the different lidar configurations: in the panel a, lidar signal profiles retrieved assuming the absence of elastic scattering and solar background are shown; in the panel b, lidar signal profiles obtained considering also the elastic scattering are shown; finally, in the panel c, lidar signal profiles during daytime (including elastic scattering and background) are shown.
The comparison in Figure 6a shows the good independence on temperature for all the CFGs since temperature variation with height does not affect the signals and, then, the retrieval of $\alpha$. Adding the contribution of the elastic aerosol scattering, a good estimation of the night-time performance for all the CFGs can be done. This is shown in Figure 6b. It is clear how the use of one grating spectrometer only does not allow us to retrieve the profile of $\alpha$ with a sufficient accuracy at a high vertical resolution. M configuration is also significantly affected by elastic aerosol scattering and the retrieval of $\alpha$ at the raw vertical resolution of 60 m is biased by cross-talk contamination. R, GS2 and GS+R show better performances and, in particular GS2 looks the more effective CFG. Adding the solar background, as reported in Figure 6c, it is possible to simulate daytime conditions. Differences between night-time and daytime profiles become more relevant above about 3 km a.g.l.. This shows that most of the CFGs have also a sufficient suppression of the background noise and can operate both during night time and daytime. Only for M and GS1 configurations, the $\alpha$ profiles are noisier and require a degradation of their effective vertical resolution. To improve the SNR, profiles of $\alpha$ have been smoothed over 11 points using a box-car average filter and are shown in Figure 6d: it is clear that the profiles of $\alpha$ obtained from M and GS1 strongly improve though the effect of cross-talk provides a still significant discrepancy between GS1 and the MUSA profiles, while the M profile strongly reduces the gap with MUSA. A further decrease in the vertical resolution might allow us to further reduce the discrepancy among MUSA, M and GS1 profiles. For this purpose, further
simulations have been performed for R configurations using two razor-edge filters, instead of one, for improving the suppression of the elastic aerosol scattering. According to the results of the ray-tracing simulations, this can allow us to obtain a suppression of the elastically backscattered radiation up to $10^4$ - $10^5$, thus reducing the cross-talk to a level that allows us to improve the retrieval of $\alpha$ profiles using M configurations.

It is also important to remark that, according to the literature (Serikov et al., 2010), higher optical efficiencies than those obtained in this simulation for GS1 and GS2 as well as a stronger cross-talk suppression ($10^{-7}$ - $10^{-8}$) has been achieved through the optimization of several factors like the grating period, groove shape, blaze angle, diffraction angle, grating technology. Grating efficiency strongly depends on these parameters.

In summary, CFGs based of only one grating spectrometer cannot be used for the retrieval of $\alpha$ profiles both during night-time and daytime conditions. Simulations also indicate that all the CFGs providing a suppression of the elastically backscattered signal in the order of $10^{-5}$ can be used to provide accurate $\alpha$ profiles based on the detection of PRRS also during daytime. Moreover, it is worth to mention that GS+R good performances show how the use of only one grating spectrometer might be sufficient for designing the receiver of a lidar for the detection of PRRS, reducing costs and the size of the system. GS+R configuration is also an opportunity to reduce the number of degrees of freedom in the lidar receiver, keeping the accuracy and the resolution of the retrieval.

![Figure 7: Comparison of the true aerosol extinction coefficient profile (MUSA) and the profile retrieved using the simulated signals for a RRL system able to detect the whole PRRS using broad interference filters with a bandwidth of 15 nm and an ideal notch filter with a bandwidth smaller than 0.2 nm and able to suppress to whole elastic aerosol backscattered signal up to $10^{-5}$](image)

A final solution simulated in the frame of this task is related to the detection of the whole PRRS using broad interference filters with a bandwidth of 15 nm (Behrendt et al., 2001). These channels are completely temperature independent and allow us to collect a larger signal. However, they could be used only if a very efficient and stable suppression or detection of the elastic aerosol backscattering is implemented. To the current state of art, according to the simulation performed for this solution, broadband channels can be implemented only if an interference filter with a bandwidth smaller than 0.2 nm, stable with temperature, is used. This might allow the detection of the elastically backscattered signal and its subtraction from the PRRS. Equivalently, a notch filter with a bandwidth...
smaller than 0.2 nm and able to suppress to whole aerosol backscattered signal up to $10^{-5}$ might be considered. Results for this configuration are reported in Figure 7. These filters are typically not able to match the mentioned requirements of light suppression and thermal stability. For both cases, filters commercially available or customized by a manufacturer should be tested and this will be part of the second part of the task work from month 36 to 48. Finally, it is important to mention that further specific refinements to each of the above discussed configurations are possible and might contribute to enhance their performance with respect to the simulated scenarios.

**Close-range telescopes**

The techniques developed, and described above, to improve Raman lidar daytime capabilities are not only based on efficient receiver systems and spectral selection units but also on the use of receivers able to minimize the region close to the ground level where the lidar signals are affected by the incomplete overlap between the lidar source and the receiver FOV, that creates problems to the retrieval of aerosol optical properties. Moreover, the laser signal backscattered from the close range is not focused on the focal plane of the telescope. This is also the case for coaxial systems. This defocusing of the close-range atmospheric targets additionally contributes to the increase the nonlinearity of the lidar signal up to several hundreds of meters from the instrument, when typical telescope diameters and focal lengths are of the order of several tens of centimeter and the FOV is typically smaller than 1 mrad.

In order to select the best option for the close-range telescope of a 355-nm RRL for the detection of daytime Raman signal, different telescope options (reflectors and refractors) have been compared with their robustness with respect to the potential problems affecting the lidar measurements in the close range.

The following telescope types have been considered:
- Matsukov F/10;
- Unobscured Gregorian F/10 (based on an off-axis parabola);
- Schmidt-Cassegrain F/5;
- Newtonian F/12;
- Aspheric F/4;
- Plano-convex (PCLX) F/4.

The following characteristics have been considered to evaluate the telescope performances:
- the sensitivity to misalignments (within 1.0 degree) and defocus (within ±100 microns) of the telescope image at the focal plane, that can be critical for detecting close-range signals since a small FOV is required for daytime operations and along with this a very good system stability is needed to guarantee that the laser beam always remains in the FOV;
- the relative illumination of the surface, normalized over the effective surface area of the receiving telescopes;
- the Huygens Point Spread Function (PSF). PSF of an optical system is the image that results from a single point source radiated from object space at the image surface. There are two main reasons that a real optical system will not image a perfect point in image space. First, aberrations from the real optical system will spread the image over a finite area. Second, even in a well corrected system with no aberrations, diffraction effects spread the image. The Huygens PSF of an optical system is computed by tracing a grid of rays from the source point to the image surface. For each ray, the
amplitude, coordinates, direction cosines, and optical path difference (OPD) are used to compute the complex amplitude of the plane wave incident at every point on the image space grid. A coherent sum for all rays is performed at every point in the image space grid, and the intensity of each point is the square of the resulting complex amplitude sum (from ZEMAX manual). In Figure 8, an example of the sensitivity to misalignments and defocus and of the calculation of the Huygens PSF for the Schmidt-Cassegrain F/5 telescope is reported.

In Table 1, the results of the comparison of the different telescopes described above are reported. In particular, in Table 1 the following characteristics of the telescopes are listed: the telescope F-number, the increase factor of the image size due to a defocus of ±100 microns, the relative illumination normalized over the entrance pupil of the telescope, the Strehl ratio provided by the calculation of Huygens Point Spread Function (PSF) and representative of the quality of optical image formation affected by lens aberrations (the Strehl ratio has a value between 0 and 1, with a "perfect" unaberrated optical system attaining the value of unity); finally, the increase of the image size on the focal plane due to misalignments and the size of the image according the geometrical ray tracing. Both defocus and misalignment are reported in terms of GEO or RMS radius; the first indicates the maximum radius containing the whole image, the second is the sum of the square of the distances of each ray from the center of the focal plane.

From Table 1, it becomes clear that the Schmidt-Cassegrain is the only telescope able to compare with refractor telescopes, since it is least sensitive to defocus and misalignments. Though it has the same illumination efficiency of a refractor, it requires an entrance pupil that is 6 times the entrance pupil of a refractor telescope. This is in conflict with those equipments that are required to be as compact as possible. The Matsukov telescope has a larger illumination efficiency but it is very sensitive to defocus and misalignments. The Newtonian telescope is not affected by critical aberration effects. Moreover, it has the higher Strehl ratio. Aspheric lenses must be preferred though they are limited as most of the refractor telescopes to the commercially available lens size, typically lower than 2 inches. Larger customized lenses might have a very high cost. It is also worth to remark that only monochromatic calculations resulting in a Strehl ratio higher than about 0.10 are considered as reliable, so this test cannot be considered reliable for the refractor telescopes.
Regarding the image size, all the systems have proven to have focalization of the images in regions smaller than 1 mm, with good performances for all the reflectors, good performance for the aspheric refractor, and less good for the single plano-convex lens.

<table>
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<tr>
<th>Telescope</th>
<th>Matsukov</th>
<th>Un. Gregorian</th>
<th>S. Cassegrain</th>
<th>Newtonian</th>
<th>Aspheric</th>
<th>PCLX</th>
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Table 1: comparison of the characteristics of different telescope configurations.

For those lidars detecting PRRS based on the separation of the polarized components of the spectrum, reflecting telescopes with a lower F-number have the potential to increase polarization cross-talk. In addition, it is good to remind that, more in general, in terms of image sensitivity to thermal variation, degrees of freedom and microroughness of the surfaces, refractor telescopes should be preferred, while reflectors must be preferred to cover a wider spectral range (Nelson et al., 2006).

References


