# Initial Report on Measurement Uncertainty Gap Analysis

***GAIA-CLIM***

*Gap Analysis for Integrated*

*Atmospheric ECV Climate Monitoring*

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## 2. Measurement Technique and Uncertainty Quantification

### 2.1 Aerosol, water vapour, ozone and temperature profiles measured by lidar (*example header)*

1) Brief description of the measurement technique and instrument

Lidar provides a method of directly measuring the optical properties of atmospheric aerosol distributions, as well as of other atmospheric parameters or components (molecules and fluorescent species, wind velocity and direction, temperature and water vapor) as *profiles*. Lidar makes use of a laser to excite backscattering in the atmosphere. This backscattered signal is observed using a telescope receiver, which collects the light and send it to the receiver optics. The role of the optical chain is to select specific wavelengths, split between them and direct them to photodetectors, which further convert the optical signal into electrical signals. These are recorded as a function of time by analog-to-digital converters and/or photon counting devices. Each lidar signal represents, therefore, the spatial variation of the measured parameter, i.e. the vertical, slant or horizontal profile of the variable.

Interaction of the laser beam with the atmosphere is complex. Multiple phenomena are produced simultaneously, both elastic (i.e. at the same wavelength: Mie and Rayleigh scattering) and inelastic (i.e. at a different wavelength: vibrational and rotational Raman, fluorescence).

Thereby, the set-up of the lidar is application-driven.

The backscatter coefficient can be measured using simple elastic backscatter lidars and several types of ceilometers, although some assumptions has to be made.

For the measurement of the extinction coefficient, inelastic (vibrational or rotational) Raman detection is generally used. The combination of the two techniques gives independent estimation of both parameters. High Spectral Resolution Lidars (HSRL) take advantage of the spectral distribution of the lidar return signal to discriminate aerosol and molecular signals and thereby measure aerosol extinction and backscatter independently.

Multi-wavelength detection is also recommended in order to extract supplementary information (e.g. intensive optical parameters such as Angstrom exponent, color indexes and color ratios, or microphysical properties such as size distribution, complex refractive index and single scattering albedo.

Lidars provide important advantages in the determination of the backscatter and extinction coefficients: high spatial resolution (1 value each 3 - 60 m), high temporal resolution (1 profile each 1 - 60 min), high dynamic range (0.2 ... 15 km). There are two important types of errors associated to the measurement of the backscatter and extinction coefficients from lidar: a) instrumental errors due to technological limitations (both at components' level and their integration); b) retrieval errors due to the non-determination of the lidar equation. Nevertheless, the quality assurance program developed by the European Aerosol Research LIdar NETwork EARLINET made possible the estimation of the backscatter and extinction profiles with an uncertainty less than 10%, which is proper for microphysical inversion and climatological studies. The range in which this uncertainty threshold is kept depends on the individual lidar systems (the signal-to-noise ratio of the channels).

Below a detailed list of the available lidar techniques for aerosol monitoring is provided:
- ceilometer
- Single-wavelength backscatter lidar
- Single-wavelength backscatter lidar + depolarization channels
- Raman lidar
- Raman lidar + depolarization channels
- High Spectral Resolution Lidar (HSRL)
- High Spectral Resolution Lidar (HSRL) + depolarization channels
- Multi-wavelength backscatter lidar
- Multi-wavelength backscatter lidar + depolarization channels
- Multi-wavelength Raman lidar
- Multi-wavelength Raman lidar + depolarization channels

Here also a list of the aerosol products that can be derived from a lidar:
- Geometrical properties
- Layer identification (top, bottom and center of mass)
- Optical properties profiles
- Extensive optical parameters: aerosol backscatter coefficient (βa), aerosol extinction coefficient (αa)
- Intensive optical parameters: Lidar ratio (S), particle linear depolarization ratio (δa), Ångström backscatter related exponent, Ångström extinction related exponent, Optical properties in the identified layer
- Integrated backscatter, AOD
- Mean intensive optical parameters (Lidar ratio, particle linear depolarization ratio, Ångström backscatter related exponent, Ångström extinction related exponent)
- Aerosol Typing classification

- Mass concentration estimate
- Microphysical properties retrieved

Below a table summarizing different capabilities for different lidar techniques aso in synergy with sun photometers:

| Ground-based Lidar techniques | Geo. properties | $b_a$ | $a_a$ | S* | AOD | $å_a$ | $å_b$ | type¥ | Microphys. prop. |
|---|---|---|---|---|---|---|---|---|---|
| ceilometer‡ | ✓ | ✓§ | | | | | | | |
| Ceilo+sun photo. | ✓ | ✓ | ✓(d) | | ✓(d) | | | | |
| Ceilo+sun photo.+ depol | ✓ | ✓ | ✓(d)[1] | | ✓(d) | | | ✓ (limited) | |
| Backscatter lidar 1-λ | ✓ | ✓ | | | | | | | |
| Backscatter lidar 1-λ + sun photo. | ✓ | ✓ | ✓(d)[1] | | ✓(d) | | | | |
| Backscatter lidar 1-λ + sun photo.+ depol | ✓ | ✓ | ✓(d)[1] | | ✓(d) | | | ✓(d) (limited) | |
| Backscatter lidar m-λ♯ | ✓ | ✓ | | | | | ✓ | | |
| Backscatter lidar m-λ♯ + sun photo. | ✓ | ✓ | ✓(d)[1] | | ✓(d) | ✓(d)[1] | ✓ | | ✓(d) [1] |
| Backscatter lidar m-λ♯ + sun photo.+ depol | ✓ | ✓ | ✓(d)[1] | | ✓(d) | ✓(d)[1] | ✓ | ✓ | ✓(d) [1] |
| 1-λ Raman lidar/HSRL | ✓ | ✓ | ✓ | ✓[2] | ✓[2] | | | ✓[2] (limited) | |
| 1-λ Raman lidar/HSRL +sun photo. | ✓ | ✓ | ✓[2] | ✓[2] | ✓[2] | ✓(d)[1] | ✓(d)[1] | ✓ (limited) | ✓(d)[1] |
| 1-λ Raman lidar/HSRL +sun photo. + depol | ✓ | ✓ | ✓[2] | ✓[2] | ✓[2] | ✓(d)[1] | ✓(d)[1] | ✓ | ✓(d)[1] |
| m-λ♯ Raman lidar | ✓ | ✓ | ✓[2] | ✓[2] | ✓[2] | ✓[2] | ✓ | ✓[2] | ✓[2] |
| m-λ♯ Raman lidar +sun | ✓ | ✓ | ✓[2] | ✓[2] | ✓[2] | ✓[2] | ✓ | ✓ | ✓[2] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| photo. | | | | | | | | | |
| m-λ♯ Raman lidar +sun photo.+ depol | ✓ | ✓ | ✓[2] | ✓[2] | ✓[2] | ✓[2] | ✓ | ✓ | ✓[2] |

Table 1: Official Request for Provision of a Table of Capabilities and Accuracies of Detection Methods based on ICAO-IVATF/2 WP05 with the following legend; □ From two independent measurements; ¥ Identification of scattering type (aerosol particles, cloud droplets, ice crystals, some aerosol type information); ‡ A ceilometer is a single-wavelength, low-power lidar, with lower S/N ratio; § if calibrated; [1] Estimate only; # m > 2; [2] Most Raman lidar systems operate during night-time. 24h Raman lidar systems exist and their operability has been proved, however few systems nowadays operate Raman channels also during daytime; HSRL is independent of daytime; d= only daytime, n= only night time.

2) Brief description of measurement procedure & analysis algorithm (incl. information needed for measurement traceability)

**All the operations and measurement procedure to be performed for aerosol lidar measurements are reported in the ACTRIS deliverable of WP2 (attached to this summary).**

Aerosols scatter and absorb both incoming and outgoing radiation (direct effect), and influence cloud formation, their microphysical properties and lifetime (indirect effect). The amount of radiation that is scattered and the directions of scatter, as well as the amount of radiation absorbed, varies with aerosol composition, size, and shape. Thus, the measurements of aerosol optical properties (aerosol backscatter and extinction coefficients at various wavelengths) contribute to the quantification of the radiative forcing, but also to the estimation of particle's physical properties, by inversion of the spectral optical data.

- The backscatter coefficient is a measure of the fraction of incident radiation that is scattered directly back toward the source.
- The extinction coefficient is a measure of attenuation of the light passing through the atmosphere due to the scattering and absorption by atmospheric components (aerosols, molecules). The extinction coefficient is the sum of the absorption coefficient and the scattering coefficient, and generally depends on wavelength and temperature.

### 2.3.3 Optical properties of aerosol and clouds

Lidar measurements are able to characterize optical properties of aerosol and clouds. Optical properties can be divided in extensive and intensive: **extensive** properties depend on both the nature and the amount of the aerosol, while **intensive** properties are independent of aerosol amount, depending only on the nature of the specific aerosol type.

#### Extensive properties

Optical extensive properties are the extinction coefficient and the backscattering coefficient.

The extinction coefficient $\alpha_\lambda(z)$ is a measure of attenuation of the light passing through the atmosphere due to the scattering and absorption by aerosol particles. $\alpha_\lambda(z)$ is the fractional depletion of radiance per unit path length (also called attenuation especially in reference to radar frequencies). It has units of $m^{-1}$.

The extinction coefficient is a combination of the scattering coefficient $\alpha_\lambda^s$ and the absorption coefficient $\alpha_\lambda^a$ of molecules (mol) and aerosol particles (par):

$$\alpha_\lambda(z)=\alpha_\lambda^{s,mol}(z)+\alpha_\lambda^{s,par}(z)+\alpha_\lambda^{a,mol}(z)+\alpha_\lambda^{a,par}(z) \qquad \text{[Eq.1]}$$

where z is the altitude range and lidar is pointing in the zenith viewing direction.
The backscatter coefficient $\beta_\lambda(z)$ is a measure of the scattering in the backward direction ( i.e. towards the incident direction, at an scattering angle of 180 deg ) for the light encountering the atmospheric aerosol particles.
The backscatter coefficient $\beta_\lambda(z)$ for elastic signals ($\lambda = \lambda_0$) can be summed up from the backscatter coefficients of molecules and particles:

$$\beta_{\lambda_0}(z)=\beta_{\lambda_0}^{mol}(z)+\beta_{\lambda_0}^{par}(z) \qquad \text{[Eq.2]}$$

The backscattering coefficients of the molecular atmosphere as well as of the aerosol particles can be calculated from the number density of the scatterers $N^{mol/par}$, their scattering cross-section $\sigma_{\lambda_0}^{mol/par}$, and the phase function $\Phi_{\lambda_0}^{mol/par}(\theta)$ for the scattering angle $\theta=\pi$:

$$B_{\lambda_0}^{mol/par} = N^{mol/par}\sigma_{\lambda_0}^{mol/par}\Phi_{\lambda_0}^{mol/par}(\pi) \qquad \text{[Eq.3]}$$

The column optical depth is also a variable ofter used to describe aerosol and clouds properties over the the full atmospheric column, and it is defined as the integral of the particle extinction coefficient from the ground to the top of the atmosphere (TOA):

$$\tau = \int_0^{TOA} \alpha^{par}(z)dz \qquad \text{[Eq.4]}$$

This definition allows to include also contribution from stratospheric aerosol if present.

**Intensive properties**

The particle lidar ratio is defined as the ratio of the particle extinction coefficient and the particle backscattering coefficient:

$$S_{\lambda_0}^{par}(z)=\frac{\alpha_{\lambda_0}^{par}(z)}{\beta_{\lambda_0}^{par}(z)} \qquad \text{[Eq.5]}$$

The lidar ratio can be derived only from profiles of $\alpha_{\lambda_0}^{par}(z)$ and $\beta_{\lambda_0}^{par}(z)$ determined in an independent way and with the same time and height resolutions. This can be obtained using the Raman technique, described in section3.2. In the case of aerosol, lidar ratio can be also estimated using the combination of co-located elastic lidar and sun photometer measurements (Mattis et al., 2004). In case of clouds at infrared wavelengths, as reported in Hogan et al. (2004), according to the Mie theory, droplet size distributions with median volume diameters in the range 5-50 µm have an approximately constant lidar ratio at 18.75 sr.
The Angström coefficient indicates the aerosol extinction coefficient dependence on the wavelength, and it is defined as (Angström, 1929):

$$\mathring{a}(z)=\log\left(\frac{\alpha_{\lambda_1}(z)}{\alpha_{\lambda_2}(z)}\right)/\log\left(\frac{\lambda_2}{\lambda_1}\right) \qquad \text{[Eq.6]}$$

where $\alpha_1(z)$ and $\alpha_2(z)$ are the aerosol extinction profiles relative to a couple of wavelength ( $\lambda_1$ and $\lambda_2$ ). As the lidar ratio, the Angström coefficient is not dependent on the aerosol concentration, but it is related to aerosol microphysical properties. It is inversely proportional to the particle size and depends on the complex refractive index of the particles. Lidar depolarization technique is a well-established method to distinguish water phase in clouds, like cirrus and mixed–phase clouds. Two different parameters can be provided with the lidar measurements (Freudenthaler et al., 2009): the linear volume depolarization ratio,

$$\delta^v(z)=\frac{\beta_\perp(z)}{\beta_\parallel(z)}=\frac{P_\perp(z)}{P_\parallel(z)} \qquad \text{[Eq.7]}$$

and the particle linear depolarization ratio,

$$\delta^{par}(z) = \frac{\beta_{\perp}^{par}(z)}{\beta_{\parallel}^{par}(z)} = \frac{(1+\delta^m)\delta^V(z)R(z) - (1+\delta^V(z))\delta^{mol}}{(1+\delta^m)R(z) - (1+\delta^V(z))} \qquad \text{[Eq.8]}$$

where $P_{\perp}(z)$ and $P_{\parallel}(z)$ are the measured perpendicular and parallel backscatter radiation intensities from the height z with respect to the transmitter polarization axis ; $\beta_{\perp}(z)$ and $\beta_{\perp}^{par}(z)$ are the total and the particle volume backscattering coefficient from the height z , respectively, with a polarization perpendicular to the polarization of the laser source; $\beta_{\parallel}(z)$ and $\beta_{\parallel}^{par}(z)$ are the total and the particle volume backscattering coefficient from the height z, respectively, with a polarization parallel to the polarization of the laser source; $\delta^{mol}$ is the height independent linear depolarization ratio of air molecules defined as,

$$\delta^{mol}(z) = \frac{\beta_{\perp}^{mol}(z)}{\beta_{\parallel}^{mol}(z)}; \qquad \text{[Eq.9]}$$

Finally $R(z)$ is the backscatter ratio, i.e the ratio of the total backscatter coefficient to the molecular component,

$$R(z) = \frac{\beta^{par}(z) + \beta^{mol}(z)}{\beta_{\parallel}^{mol}(z)} \qquad \text{[Eq.10]}$$

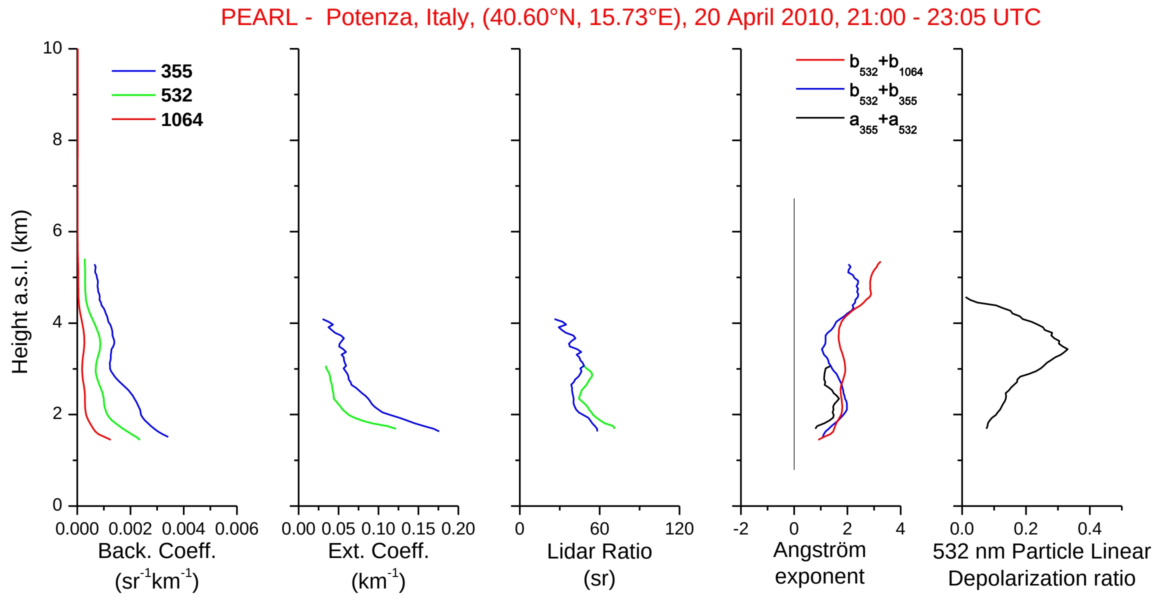


Figure 1: Example of the retrieval of extensive and intensive optical properties obtained with PEARL (Potenza EArlinet Raman Lidar) multi-wavelength lidar system operative at Potenza, Italy, in the frame of EARLINET (European Aerosol Research LIDar NETwork).

The estimation of $\delta^{par}(z)$ and $å(z)$ represent the added value of lidar profiling measurements towards the typing of observed particles as a function of the range. The study of depolarization allows us to obtain important information about the particle shape: along with the multi-wavelength backscattering and extinction measurements and the information provided by isentropic back-trajectories, the aerosol depolarization ratio allows to discriminate the nature of the observed particles and to classify them with respect to the source regions. Moreover, observations of the linear depolarization ratio at several

wavelengths may be used in retrieval schemes (Dubovik et al., 2006) to improve the estimation of the microphysical properties of dust from optical measurements (Wiegner et al., 2008).
An example of the retrieval of extensive and intensive optical properties obtained with PEARL (Potenza EArlinet Raman Lidar) multi-wavelength lidar system operative at Potenza, Italy, in the frame of EARLINET (European Aerosol Research LIDar NETwork) is reported in Figure 1. The retrieval is referred to the observation to the aerosol outbreak over Europe due to the volcanic eruption of Eyjafjallajökull, a small volcano under Iceland's ice cap (Mona et al., 2012).

### 2.3.4 Inversion methods

Lidar equation is the way to relate the light power backscattered by the atmospheric target with the signal collected by the lidar receiver. In a general form, lidar equation can be written as

$$P(\lambda_L,\lambda_S,z)=P_L(\lambda_L)\Psi(\lambda_S,\lambda_L)O(z)\beta(\lambda_S,\lambda_L,\theta,z)\frac{A}{z^2}\frac{c\tau_d}{2}\exp\left(-\int_0^z\alpha(z)dz\right)+P_B \qquad \text{[Eq.11]}$$

where:
$P(\lambda_L,\lambda_S,z)$ is the backscattered power received from the distance $z$ from the source (zenith pointing), at a specific polarization and wavelength $\lambda_s$, due to the scattering of the laser wavelength $\lambda_L$;
$\Psi(\lambda_S,\lambda_L)=\xi(\lambda_L,\lambda_S)\eta(\lambda_S)$ is transmission of the lidar receiver, given by $\xi(\lambda_L,\lambda_S)$ that is the optical efficiency of the lidar receiver, including such factors as the reflectivity of the telescope and the transmission of the conditioning optics, while $\eta(\lambda_S)$ is the quantum efficiency of the receiver and detection parts;
$O(z)$ is the system overlap function;
$P_L(\lambda_L)$ is the output laser power at the wavelength $\lambda_L$;
$\beta(\lambda_S,\lambda_L,\theta,z)$ is the volume scattering coefficient at the distance $z$ and at an angle θ and represents the probability that a transmitted photon is backscattered by the atmosphere into a unit solid angle ($\theta=\pi$);
$\frac{A}{z^2}$ is the probability that a scatter photon from the distance is collected by the receiving telescope of surface A;
$\frac{c\tau_d}{2}$ represents the sounding vertical resolution, where $c$ and $\tau_d$ are respectively the light speed and the dwell time (i.e. the laser duration pulse);
$\exp\left(-\int_0^z\alpha(z)dz\right)$ is the two-way transmissivity of the light from laser source to the distance $z$ and from distance $z$ to the receiver, respectively;
$P_B$ is the contribution power return due to the background photons.
To use of [Eq.11] for the inversion of the backscattered radiation and to retrieve the atmospheric parameters, the approximation of single and independent scattering is needed: this means that a photon is scattered only once by the atmospheric constituents and that these are separated adequately and are moving randomly. Thus, the contribution to the total scattered energy by many targets have no phase relation and the total intensity is simply the sum of the intensity scattered from each target.
The inversion of lidar equation can be performed using different methods depending on the availability of the elastic signal only or the also the Raman signal. The method more frequently applied are described in the next section.

**Backscattering coefficients from an elastic signal**

The calculation of the backscattering coefficients from an elastic signal can be performed using different methods. In the following the Klett-Fernald and iterative methods are described.

**Klett method**

One of the most common method to derive extinction coefficient form elastic lidar measurements is the so-called Klett inversion method is used [Ansmann et al., 1990]. This method, however, has the disadvantage that two physical quantities, the aerosol backscatter and extinction coefficients must be determined from only the elastic backscatter. This is not possible without assumptions about the relationship between the two and an estimate of a reference value of the aerosol extinction.

One of the possible variant of Klett method [Klett, 1981, Fernald, 1984], $\beta^{par}_{\lambda_0,i}(z)$ can be obtained as

$$\beta^{par}_{\lambda_0}(z) = -\beta^{mol}_{\lambda_0}(z) + \frac{A(z, z_{ref})}{B(z_{ref}) + 2\exp\left(-2\int_z^{z_{ref}} S^{par}_{\lambda_0}(z')A(z', z_{ref})dz'\right)} \quad \text{[Eq.12]}$$

In the [Eq.12], we have:

$$A(x, z_{ref}) = P_{\lambda_0}(z)z^2 \exp\left(2\int_x^{z_{ref}} \left(S^{par}_{\lambda_0}(x') - S^{mol}\right)\beta^{mol}_{\lambda_0}(x')dx\right) \text{ with } x = z, z_{ref},$$

$$B(z_{ref}) = \frac{P_{\lambda_0}(z_{ref})z^2_{ref}}{\beta^{par}_{\lambda_0}(z_{ref}) + \beta^{mol}_{\lambda_0}(z_{ref})},$$

$z_{ref}$ is a reference range assumed in an aerosol-free region:

**Iterative method**

The iterative method is described e.g., by Di Girolamo et al. [1999]. The particle backscatter coefficient

$$\beta^{par}_{\lambda_0,i}(z) = \left(\frac{P^{par}_{\lambda_0}(z)K_{\lambda_0,i}}{P^{mol}_{|\lambda_0,i|}(z)} - 1\right)\beta^{mol}_{\lambda_0}(z) \quad \text{[Eq.13]}$$

is calculated in the i-th iteration step from the measured, pre-processed, overlap-corrected signal and an estimated molecular signal, expressed as:

$$P^{par}_{\lambda_0}(z) = \frac{P_{\lambda_0}}{O(z)}$$

$$P^{mol}_{\lambda_0,i}(z) = \beta^{mol}_{\lambda_0}(z)\exp\left(-2\int_0^z S^{par}(z')\beta^{par}_{\lambda_0,i-1}(z')dz'\right)$$

$K_{\lambda_0,i}$ is a calibration factor and can be determined in an aerosol-free region $z_{ref}$:

$$K_{\lambda_0,i} = \frac{P^{mol}_{\lambda_0,i}(z_{ref})}{P^{par}_{\lambda_0}(z_{ref})}$$

A proper profile $S^{par}(z)$ or a height-independent value $S^{par}$ of the lidar ratio has to be assumed. In an initial step the molecular signal $P^{mol}_{\lambda_0,0}(z)$ is estimated with the assumption $\beta^{par}_{\lambda_0}(z) = 0$ and is then used to derive an initial value of $\beta^{par}_{\lambda_0,0}(z)$. In the following iteration step i the backscatter coefficient $\beta^{par}_{\lambda_0,i}(z)$ is calculated from a molecular signal which is estimated from the previous backscatter profile $\beta^{par}_{\lambda_0,i-1}(z)$. This procedure is repeated until the difference between $\beta^{par}_{\lambda_0,i}(z)$ and $\beta^{par}_{\lambda_0,i-1}(z)$ is smaller than a certain threshold.

**General considerations**

The retrieval of the backscattering coefficient using only the elastic signals is affected by sources of uncertainties. Over those affecting all the lidar retrievals, there are two additional large sources of uncertainty due to:

1. uncertainty due to the assumption of a particle lidar ratio (profile); this uncertainty can easily exceed 20% [Sasano et al., 1985], as shown in figure 2, where profiles of the backscattering coefficient obtained using the iterative method assuming a lidar ratio equal to 30, 50 and 80 sr, respectively, are compared with the results of the Raman/Elastic combined retrieval.

2. uncertainty in the lowest part of the profile due to the incomplete overlap between laser beam and receiver field of view (Mattis et al., 2007) and the necessity to correct measured signals with the overlap function O(z) .

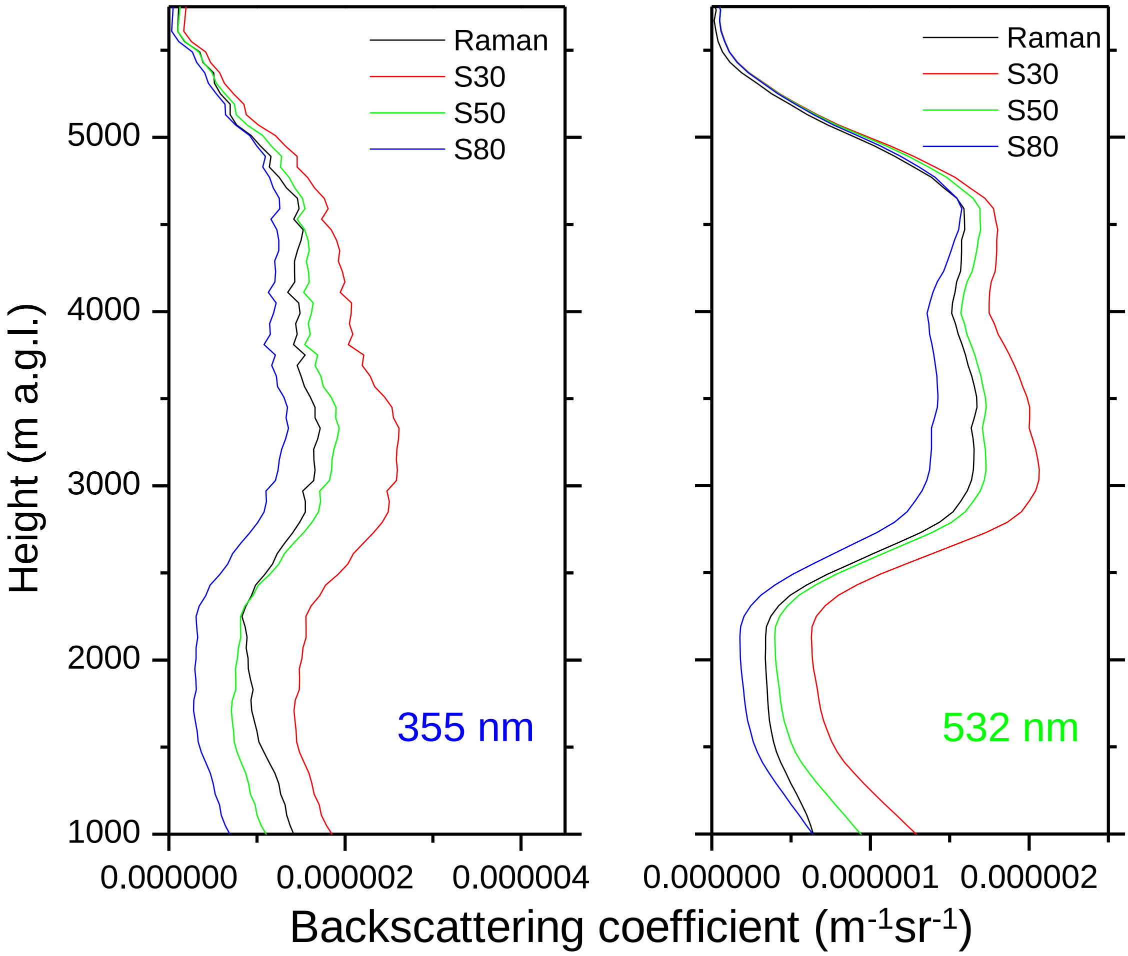


Figure 2: Example of the effect of lidar ratio assumption in the iterative method for the inversion of lidar equation. Black line is the profile obtained using the Raman/elastic combined technique, red line is the profile obtained using the iterative method with a lidar ratio of 30 sr, green line is the same with a lidar ratio of 50 sr, and red line with a lidar ratio of 80 sr. Left panel reports the comparison at 355 nm and the right panel the comparison at 532 nm.

**Backscatter and extinction coefficients using elastic and Raman signals.**

The Raman/elastic combined technique provides independent estimations of the aerosol backscattering and extinction profiles avoiding the assumptions necessary to invert the lidar equation in the elastic case (Pappalardo et al., 2004). In this case, the molecules change their initial states to different final states and the scattered light experiences a frequency shift due to vibrational-rotational Raman shift or pure rotation Raman shift. The inelastic Raman backscatter signals are affected by the aerosol attenuation but they are independent on the aerosol backscatter, then it is possible to retrieve the aerosol extinction coefficient $\alpha^{a}(z)$, for example using as reference the nitrogen (or also the oxygen) Raman return. In fact, the nitrogen has a well-known distribution in the atmosphere. Therefore, making the logarithm and the derivative of the [Eq. 11], we obtain:

$$\frac{d}{dz}\left[\ln\left(\frac{n_R(z)}{P(\lambda_R,z)z^2}\right)+\ln\left(P_L A_0\frac{c\tau_d}{2}\Psi(\lambda_L,\lambda_R)\frac{d\sigma(\lambda_R)}{d\Omega}\right)\right]=\alpha_{\lambda_L}^{mol}(z)+\alpha_{\lambda_L}^{par}(z)+\alpha_{\lambda_R}^{mol}(z)+\alpha_{\lambda_R}^{par}(z)$$

and then solving with respect to the extinction of particles

$$\alpha_{\lambda_L}^{par}(z)+\alpha_{\lambda_R}^{par}(z)=\frac{d}{dz}\left\{\ln\left[n_R(z)/P_{\lambda_R}(z)z^2\right]\right\}-\alpha_{\lambda_L}^{mol}(z)-\alpha_{\lambda_R}^{mol}(z) \qquad \text{[Eq.14]}$$

where we have made explicit the nitrogen backscattering cross-section as the product of the differential backscattering cross-section $\frac{d\sigma(\lambda_R)}{d\Omega}$ and the number of scatters $n_R(z)$. The wavelength dependence of the aerosol extinction coefficient is described by the Ångström coefficient, å , defined from the relation $\frac{\alpha_{\lambda_L}^{par}(z)}{\alpha_{\lambda_R}^{par}(z)}=\left(\frac{\lambda_R}{\lambda_L}\right)^{å}$ . Ansmann (1992) showed that this dependence is lower than 1% and thus it can be considered as negligible. Finally, resolving the [Eq.14] with respect to $\alpha_{\lambda_L}^{par}(z)$, we have:

$$\alpha_{\lambda_L}^{par}(z)=\frac{\frac{d}{dz}\left\{\ln\left[n_R(z)/P_R(z)z^2\right]\right\}-\alpha_{\lambda_L}^{mol}(z)-\alpha_{\lambda_R}^{mol}(z)}{1+\left(\lambda_L/\lambda_R\right)^{å}} \qquad \text{[Eq.15]}$$

$\beta_{\lambda_0}^{par}(z)$ can be derived directly from the ratio of the Raman signal at $\lambda_{N_2}$ and the elastic signal at $\lambda_L$ (Ansmann et al, 1992) as:

$$\beta_{\lambda_L}^{par}(z)=-\beta_{\lambda_L}^{mol}(z)+\left[\beta_{\lambda_L}^{par}(z_{ref})+\beta_{\lambda_L}^{mol}(z_{ref})\right]\frac{O_{\lambda_R}(z)}{O_{\lambda_L}(z)}\frac{P_{\lambda_R}(z_{ref})}{P_{\lambda_L}(z_{ref})}\frac{P_{\lambda_L}(z)}{P_{\lambda_R}(z)}\frac{\beta_{\lambda_L}^{mol}(z)}{\beta_{\lambda_L}^{mol}(z_{ref})}\exp(C) \qquad \text{[Eq.16]}$$

with $C=\left(1-\left(\frac{\lambda_L}{\lambda_R}\right)^{å}\right)\left(\int_{z_{ref}}^{z}\alpha_{\lambda_L}^{par}(z')dz'\right)$. $z_{ref}$ is a reference altitude assumed aerosol free.

Alternatively, Ferrare et al. [1998] suggested another way to derive $\beta_{\lambda_L}^{par}(z)$ calculating first the backscattering ratio:

$$R(z)=\frac{\beta^{par}(z)+\beta^{mol}(z)}{\beta_{\parallel}^{mol}(z)}=F^{\beta}\ \frac{O_{\lambda_R}(z)}{O_{\lambda_L}(z)}\frac{P_{\lambda_L}(z)}{P_{\lambda_R}(z)}\exp\left[\left(1-\left(\frac{\lambda_L}{\lambda_R}\right)^{å}\right)\exp\left(-\int_0^z\alpha_{\lambda_L}^{par}(z')dz'\right)\right] \qquad \text{[Eq.17]}$$

$F^{\beta}$ is a calibration factor. Then $\beta^{par}(z)$ can be derived as:

$$\beta^{par}(z)=\beta_{\lambda_L}^{mol}(z)(R(z)-1)$$

The advantage of this method is that it theoretically allows for an absolute calibration of the lidar system. If the calibration factor $F^{\beta}$ is derived once under optimal atmospheric conditions (clean free troposphere), it can be applied to all other measurements under arbitrary conditions as long as the system configuration does not change.

3) Brief description of the method used to calculate the uncertainties (uncertainty quantification)

Two kinds of errors are associated to the retrieval of the backscatter and extinction from lidar measurements: random errors (typically named statistical in the lidar community) and systematic errors.

1. Random errors are mainly due to the to signal detection, i.e. background of sky and dark current of detector (Theopold and Bösenberg, 1988). Directly related to this kind of error, there is the error introduced by operational procedures such as signal averaging during varying atmospheric extinction and scattering conditions (Ansmann et al., 1992; Bösenberg, 1998). Statistical errors can be assessed either by analytical propagation (Gaussian or Poison statistical distributions have to be considered), either by Monte Carlo techniques.

2. Systematic errors generally arise from:

a) the estimation of temperature and pressure profiles (Ansmann et al., 1992);

b) the estimation of the ozone profiles in the UV (Ansmann et al., 1992) and in other spectral ranges;
c) the wavelength dependence parameter k (Ansmann et al., 1992; Whiteman, 2000);
d) the multiple scattering (Ansmann et al., 1992; Wandinger, 1998; Whiteman, 2000);
e) the overlap function (Wandinger and Ansmann, 2002).
Systematic errors are more difficult to estimate and this is still an open scientific issue though several solution have been already proposed and tested

There are also a few uncertainties related to operational performance and technical implementation
Although lidar technique has been used for many years, recent technological developments, coupled with the implementation of modern mathematical procedures have led to a more operative use of lidar systems. Ceilometers are nowadays more and more complex and sensitive, some new products being able to detect aerosols and therefore to deliver the backscatter coefficient with the coupling of other sensors and with a large error (more than 50%). On the other hand, powerful lidars are more and more automatic and suitable for a 24/7 unmanned operation. Elastic lidars equipped with nitrogen Raman detection channel are intermediate solutions for an accurate self-calibration and an independent retrieval of backscatter and extinction coefficient profiles without any coupling to other sensors. New industrial and operational nitrogen Raman lidars based on diode-pump lasers have shown a low maintenance and a high data availability. The main progresses recorded in the last years are referring to the improvement of the instruments and retrieval algorithms for:
1. the automation of the operation
From an operational point of view, alignment of the laser beam into the receiver FOV is critical. Depending on the configuration, the overlap control needs to be very precise (order of 0.01 mrad) and stable with temperature. Short term fluctuations in the laser energy are usually averaged out during the integration time of the measurement. However, long term drift in the laser energy is important if the lidar is to be kept running for longer periods of time. Therefore, laser energy should be at least monitored and eventually stabilized. In case harmonics of the fundamental laser frequency are used, conversion crystals are used (SHG, THG) that alter the direction of the outgoing laser beam when they are tuned. This has to be compensated for in order to keep the overlap properly aligned. If the (generally non-eye safe) lidar is to be kept running for longer periods of time, in particular if the operator is not present from time to time, safety precautions have to be taken according to proper use of lasers outdoors. Remote control of the lidar operation (e.g. via web tools) is an option.
2. the improvement of the dynamic range
Telescopes with large apertures for high troposphere and stratosphere exploration tend to have large focal lengths, which tends to reduce field of view and increase the distance at which field full overlap is reached. To overcome this problem, two receiver sets, using different telescopes (one for far range, another, with smaller aperture, shorter focal length and nearer full overlap distance, for close range), can be used. Other solutions based on specific optical components are also available in order to reduce the overlap and ensure the highest range as possible.
Measurements can also be corrected under the full overlap height if the overlap function of the system has been measured. Increased dynamic range can be achieved also with combined analog and photon counting techniques.

3. the improvement of the temporal coverage
Daytime performance of (vibrational) aerosol Raman lidar can be achieved by sufficiently suppressing the daytime background and/or by increasing the emitter power. Narrowing down interference filter passband has consequences for the optical design of the receiver (angular dependence of the position of the passband transmission peak). Other solutions exist, e.g. grating spectrometers, tilt slit diaphragm. The limited acceptance angle of small bandwidth interference filters IFF determines the whole lidar optics design.
Ceilometer detection and inversion capabilities are also limited to the lowest part of the troposphere (up to 4-5 km) in daytime conditions.

4. reducing the uncertainties of the final products

The minimum recommendation for an optimized product is to add a nitrogen Raman channel to a backscatter lidar, so that both the backscatter and the extinction coefficient can be derived independently. The same can be achieved by using a HSRL system and / or a scanning lidar (multiple zenith-angle measurements). This latter technique requires a strong assumption on horizontal and temporal stability of the atmosphere. Moreover their use in operational networks has to be demonstrated. The implementation of state-of-the-art algorithms and tools for the correction of the signal as well as for the inversion of the corrected signal contributes both to reducing the uncertainties and to increasing the availability of the data. This includes:

- signal pre-processing: cloud screening, pile-up correction, estimation of the statistical error, background subtraction, range correction, handling of signals measured at angle different from zenith, correction for depolarization-dependent receiver transmission, calculation of the profile of the Rayleigh-scattering coefficient, correction for Rayleigh-transmission, temporal averaging to create fixed time intervals, vertical smoothing up to a fixed height resolution
- calculation of the extinction coefficient from the Raman signal: calculation of the derivative, estimation of the uncertainty of the derived extinction, determination of the overlap function
- calculation of the backscatter coefficient from combined elastic - Raman signals: detection of the reference height, estimation of the reference value

Significant improvements can be achieved by the automation of the lidar inversion, to avoid human error and operator subjectivity as done in the EARLINET Single Calculus Chain (D'Amico et al., 2015 AMTD).

Finally, smoothing and numerical derivative are typically used in the retrieval of aerosol optical properties from lidar data and both may act as low pass filter. (Iarlori et al., 2015 AMTD). As a consequence, this implies that each filter's output, at a given range (or time) in our case, will be the result of a linear combination of several lidar input data relative to different ranges (times) before and after the given range (time): a first hint of loss of resolution of the output signal and a correlation between the different height levels of the vertical profile. This would require the final representation of the uncertainty of the data using a covariance matrices, never implemented so far in the lidar community since considered a redundant information.