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

Deliverable D20.9: Retrieval of non-spherical aerosol particles properties from combined sun-photometer and depolarization lidar

Objectives and overview

Modern lidar technology allows performing measurements of polarization state of the backscatter together with elastic backscatter. For the moment there is a significant number of lidar systems that are equipped with polarization channels. The most wide spread lidar systems perform elastic backscatter measurements at wavelengths of the YAG laser (355, 532 and 1064 nm) together with cross-polarized backscattering at 532 nm, or perform elastic measurements at 355 and 1064 nm together with cross- and parallel polarized backscatter at 532nm, all oriented in relation to the polarization of the emitted laser beam.

Introducing backscattering polarization observations allows retrieving vertical profiles of aerosol depolarization (e.g. Chaikovsky et al., 1990) which values could be used to detect the presence of irregularly shaped particles, for e.g. desert dust (Veselovsky et. al, 2010, Müller et. al, 2013). Also, there are developments focused on estimation of properties of ice cloud particles on the base of observations of lidar depolarization profiles (Sassen, 1991).

Estimation of aerosol depolarization from polarized sounding includes differentiation of lidar signals ratio. In the presence of noise such solution of lidar equation relative to aerosol depolarization becomes an ill-posed problem. The methods to resolve this issue could are applicable only in special situations with long accumulation time, at low altitude resolution, and only for the stable layers with high loading of non-spherical particles.

Standardised processing of lidar network observations requires a more sophisticated algorithm that allows searching for physical solutions and preserving high altitude resolution of the retrieved aerosol characteristics under situations with low aerosol optical thicknesses and in the presence of noise in polarised signals. Such data could be treated using statistically optimized algorithms with use of adequate a priori constraints. The review of inversions techniques can be found in Turchin (1971) and Tarantolla (1987).

1. General description of the inversion algorithm

The algorithm for retrieval of optical and microphysical properties of atmospheric aerosols from combined sun-photometer and polarization measurements of a lidar could be divided into several independent modules with particular functions, whose interactions are minimized to straightforward exchange of limited set of parameters (see Fig.1).

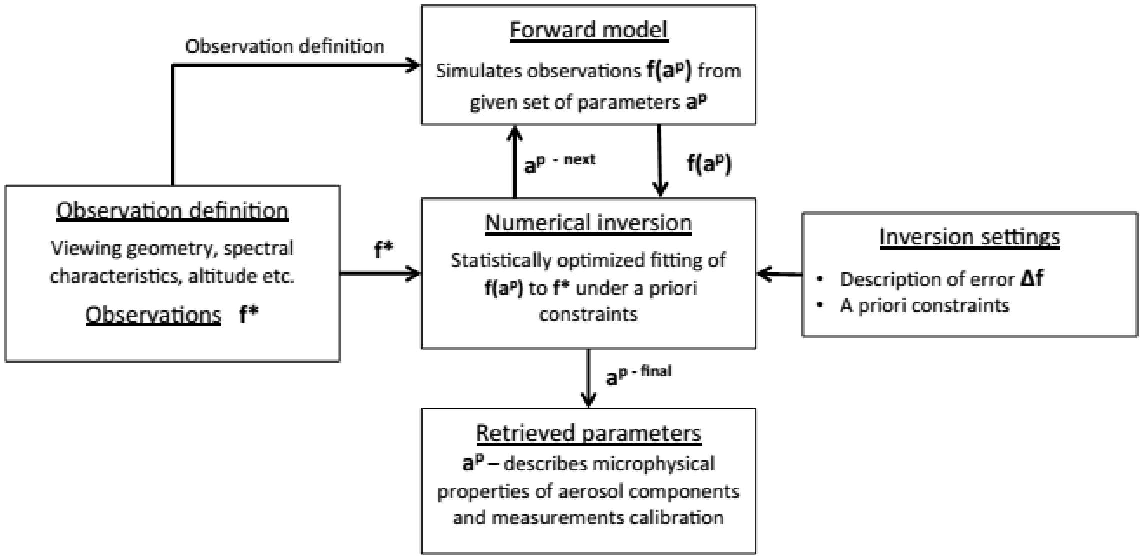

Figure 1. General structure of combined sun-photometer/Raman lidar retrieval algorithm (adapted from D20.7 deliverable).

The **forward model** of scattered radiances measured by complex AERONET and lidar observations contains four main components (as shown in Fig. 2):

• aerosol single scattering,
• aerosol optical properties vertical profiling,
• lidar equation and
• vector radiative transfer equation.

The modelling of **aerosol single-scattering** columnar optical properties and simulation of sun-photometer measurements already provide capabilities of simulations of polarized observations. First one was developed to model the particles as a mixture of spherical and non-spherical aerosol components (see Dubovik and King (2000) and Dubovik et al. (2002, 2006)), and successive order of scattering radiative transfer code allows calculations of atmospheric radiances for the aerosol composed by several components (k) (see Lenoble et al., 2007). This allows representing aerosol as a combination of three components – fine particle, coarse spherical particles and coarse non-spherical particles.

Each aerosol component is described by altitude independent phase matrix $P_{ij}^{k}(\lambda,\theta)$ and single-scattering albedo $\omega_0^k(\lambda)$ determined on the base of microphysical model of atmospheric aerosol together with the vertical profile of aerosol concentrations $c_k(h)$ which determines the vertical variability of spectral extinction $\sigma_a^k(\lambda,h)$ of atmospheric aerosol. Correspondingly, only set of parameters describing aerosol microphysics and is directly included in the set of retrieved parameters. Specifically, the vertically invariant is driven by: the shape of the size distribution $dV(r_i)/d\ln r$; the real $n_k(\lambda)$ and imaginary $\kappa_k(\lambda)$ parts of the complex refractive index. To lessen the amount of parameters used to describe aerosol model in the presence of polarized measurements the vertically constant properties for spherical and non-spherical particles (i.e. size distribution and complex refractive index are assumed to be the same). The algorithm deals with normalized functional $c_k(h)$ (see deliverable 20.7 for details), which shows the vertical partitioning of integral characteristics such as aerosol concentration and extinction.

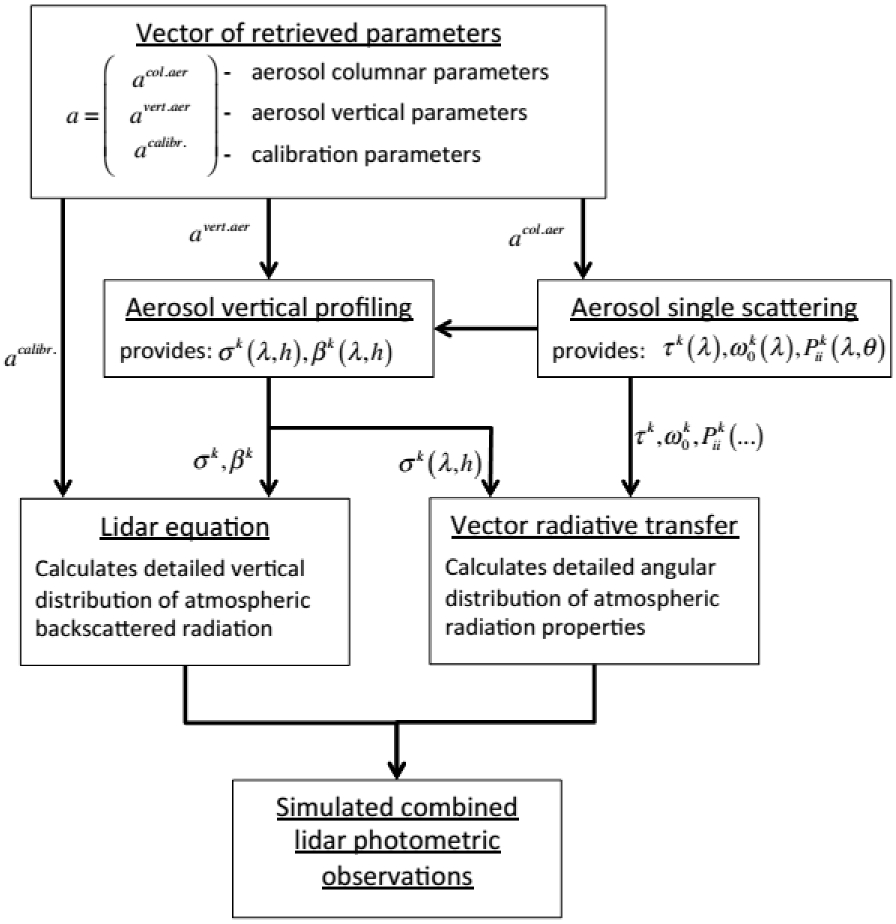

Figure 2. General scheme of forward modelling of combined sun-photometer/multi-wavelength Raman lidar observations.

Vertical profiling of aerosol extinction coefficient is achieved by the following equation:

$$\sigma_a(\lambda,h) = \tau_f(\lambda)c_f(h) + \tau_c^s(\lambda)c_c^s(h) + \tau_c^{ns}(\lambda)c_c^{ns}(h). \quad (1)$$

And aerosol backscatter coefficient for cross and parallel polarization channels are defined as follows:

$$\beta_\perp^a(\lambda,h) = \frac{1}{4\pi}\left(\sum_i \frac{P_{11}^i(\lambda,180°) - P_{22}^i(\lambda,180°)}{2}\,\omega_0^i\,(\lambda)\tau_i(\lambda)c_i(h)\right), \quad (2)$$

$$\beta_\parallel^a(\lambda,h) = \frac{1}{4\pi}\left(\sum_i \frac{P_{11}^i(\lambda,180°) + P_{22}^i(\lambda,180°)}{2}\,\omega_0^i\,(\lambda)\tau_i(\lambda)c_i(h)\right), \quad (3)$$

where i denotes one of the aerosol modes (fine, coarse spherical and coarse non-spherical), $\tau_i, \omega_0^i, P_{11}^i, P_{22}^i$ – optical thickness, single scattering albedo and elements of the phase matrices if the corresponding modes.

The following **lidar equations** are used to model the attenuated backscatter provided by polarization channels of a lidar (Chaikovsky et al., 1990):

$$L_{\perp}(\lambda,h)=\frac{\left(\beta_{\perp}^{a}(\lambda,h)+\mu\beta_{\parallel}^{a}(\lambda,h)+\frac{\chi+\mu}{\chi+1}\beta_{m}(\lambda,h)\right)}{\frac{\chi+\mu}{\chi+1}\beta_{m}(\lambda,h)}\exp\left(-2\int_{h_{ref}}^{h}\sigma_{a}\left(\lambda,h'\right)dh'\right), \quad (4)$$

$$L_{\parallel}(\lambda,h)=\frac{\left(\beta_{\parallel}^{a}(\lambda,h)+\frac{1}{\chi+1}\beta_{m}(\lambda,h)\right)}{\frac{1}{\chi+1}\beta_{m}(\lambda,h)}\exp\left(-2\int_{h_{ref}}^{h}\sigma_{a}\left(\lambda,h'\right)dh'\right), \quad (5)$$

where σ_a denotes aerosol extinction coefficient, $\beta_{\perp}^{a}, \beta_{\parallel}^{a}$ – backscatter coefficients for cross- and parallel polarized components correspondingly, β_m – backscatter coefficient of Rayleigh scatetring, χ – depolarization rate of Rayleigh scattering, μ – parameter that describes the cross-talk between cross- and parallel polarized components of lidar observation. Values of β_m and χ are known from the models of molecular atmosphere (Young, 1982), μ is known from the lidar system calibration (Behrendt, 2002).

The **numerical inversion** block is generally universal, and could be used for different configurations of remote sensing observations. Its purpose is to retrieve the vector describing microphysical properties of the atmospheric aerosol:

$$a=\begin{pmatrix} a_v \\ a_n \\ a_k \\ a_{sp\_h} \\ a_{ns\_h} \\ a_A \end{pmatrix}, \quad (6)$$

where $a_v, a_n, a_k, a_{sp\_h}, a_{ns\_h}, a_A$ denote the components of the vector of aerosol properties **a**, corresponding to size distribution, real and imaginary part of refractive index, vertical profiles of spherical particles concentration, vertical profile of non-spherical particles fraction and lidar calibration coefficient A. All of the parameters listed above describing microphysical state of the aerosol in the atmosphere, except for the lidar calibration parameters and profile of non-spherical particles fraction, consist of two subsets of parameters, each describing independent aerosol component, corresponding to fine and coarse aerosol mode:

$$a_{\dots}=\begin{pmatrix} a_{\dots}^{f} \\ a_{\dots}^{c} \end{pmatrix}.$$

Inversion is considered as a multi-term Least Squares Method (LSM) that solves the following system of equations (Dubovik and King, 2000; Dubovik et al., 2011):

$$\begin{cases} f^{*}=f(a)+\Delta f \\ 0^{*}=(\Delta a)^{*}=Sa+\Delta(\Delta a), \\ a^{*}=a+\Delta a^{*} \end{cases} \quad (8)$$

where f^* is a vector of the combined measurements, Δf is a vector of measurement uncertainties and a is a vector of unknowns.

The second term represents the a priori smoothness assumptions used to constrain the variability of size distribution, vertical concentration and spectral dependencies of the real and imaginary parts of the refractive index. The matrix S includes the coefficients for calculating *m*-th differences (numerical equivalent of the derivatives) of $dV(r_i)/d\ln r$, $c_k(h)$, $n_k(\lambda)$ and $\kappa_k(\lambda)$; 0^* is the vector of zeros and $\Delta(\Delta a)$ is the vector of the uncertainties characterizing the deviations of the differences from the zeros. The third part includes the vector of a priori estimates a^* and Δa^* is the vector of the uncertainties in a priori estimates. The errors Δf, $\Delta(\Delta a)$, and Δa^* are assumed to be normally distributed (see deliverable 20.7 for additional details).

The vector of combined sun-photometer and multi-wavelength lidar with depolarization measurement, depending on the type of lidar aqusition system used could be considered as consistent of six components, representing independent measurements with different level of accuracies:

$$f^* = \begin{pmatrix} f_\theta \\ f_\tau \\ f_{\beta_1} \\ f_{\beta_2} \\ f_{\beta_\perp} \\ f_{\beta_3} \end{pmatrix} \quad \text{or} \quad f^* = \begin{pmatrix} f_\theta \\ f_\tau \\ f_{\beta_1} \\ f_{\beta_\parallel} \\ f_{\beta_\perp} \\ f_{\beta_3} \end{pmatrix}, \tag{9}$$

where index θ denotes sun and sky radiances, τ stands for optical thickness, $\beta_{\dots}$ is for elastic lidar measurements at three different wavelengths, and $\beta_\perp, \beta_\parallel$ are for lidar measurements with corresponding polarization. These measurements are made with different accuracy and under assumption that observations are uncorrelated and provide equally accurate data (i.e. weighting matrices are equal to unity matrices) covariance matrices will have the following array structure:

$$C_f = C_f = \begin{pmatrix} \varepsilon_\theta^2 I & 0 & 0 & 0 & 0 & 0 \\ 0 & \varepsilon_\tau^2 I & 0 & 0 & 0 & 0 \\ 0 & 0 & \varepsilon_{\beta_1}^2 I & 0 & 0 & 0 \\ 0 & 0 & 0 & \varepsilon_{\beta_{\dots}}^2 I & 0 & 0 \\ 0 & 0 & 0 & 0 & \varepsilon_{\beta_\perp}^2 I & 0 \\ 0 & 0 & 0 & 0 & 0 & \varepsilon_{\beta_3}^2 I \end{pmatrix}. \tag{10}$$

The **a priori constraints** are applied in the developed algorithm on several different components of the vector a differently, same as in previous approaches (Dubovik and King, 2000; Dubovik, 2004; Dubovik et al., 2011). Two types of the constraints could be applied both together and separately: smoothness constraints, which limit the variation of the retrieved parameters and direct constraints, which limit their value. Considering the Eq. 10 the smoothness matrix will have the following form:

$$Sa = \begin{pmatrix} S_v & 0 & 0 & 0 & 0 & 0 \\ 0 & S_n & 0 & 0 & 0 & 0 \\ 0 & 0 & S_\kappa & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{sp\_h} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{ns\_h} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} a_v \\ a_n \\ a_k \\ a_{sp\_h} \\ a_{ns\_h} \\ a_A \end{pmatrix}. \tag{11}$$

The correspondent matrices $S_{\dots}$ have different dimension and represent differences of different order (3 for size distribution and for vertical profiles of aerosol concentration and (both for spherical and non-spherical particles), 1 for real part of complex refractive index and 2 for imaginary part of complex refractive index). The lines corresponding to A contain only zeros because no smoothness constraints are applied on them.

Direct application of a priori constraints on the values of the retrieved vector could be useful in specific situation, when estimations of the values of vector of parameter **a** are already known (see deliverable 20.7 for description).

2. Development of LiRIC program package for retrieving non-spherical aerosol particles vertical concentration from processing of combined polarized lidar and radiometer data

Additional program modules have been developed for processing data of combined multi-wavelength Raman and radiometer data. The structure of the second version of improved program package LiRIC is shown in the Figure 3. The second version of LiRIC includes three program modules for retrieving profiles of aerosol mode concentrations (“**ConcentRetriver”,** described in Deliverable WP20/D20.4), extinction/lidar ratio (“**RamanRetriver**”, described in deliverable D20.7**)** and depolarization ratio (“**PolarizRetriever”**).

The retrievals of vertical profile of non-spherical particles concentration, was used in several recent studies (e.g. Wagner et. al., 2013, Tsekeri et. al, 2013). The examples of retrievals performed for the measurements obtained during the Eyjafjallajökull eruption can be seen in Figs. 4 and 5.

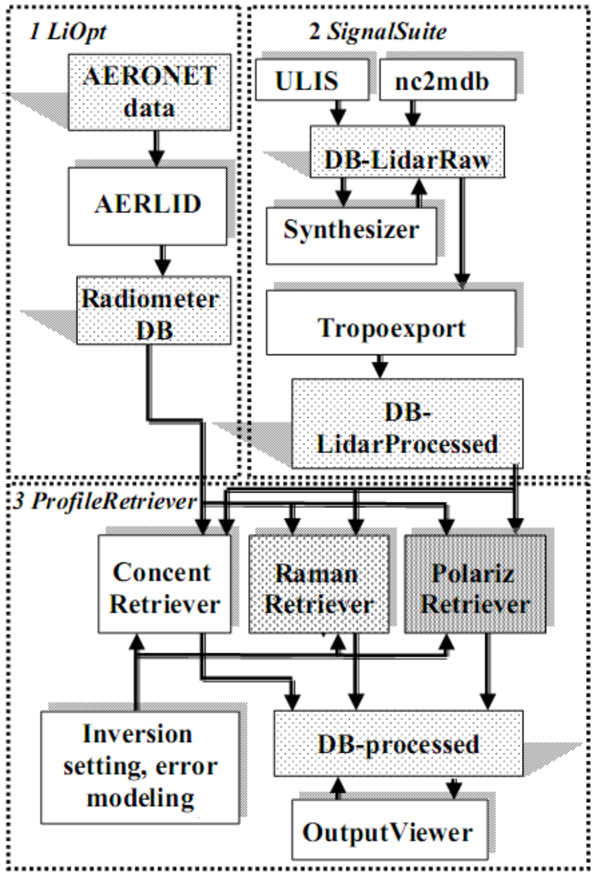

Figure 3. Structure of the second version of LiRIC program package. Current status of retrieving modules: ***ConcentRetriver*** *and* ***RamanRetriever*** *is in operational mode,* ***PolarizRetriver*** *is in test mode.*

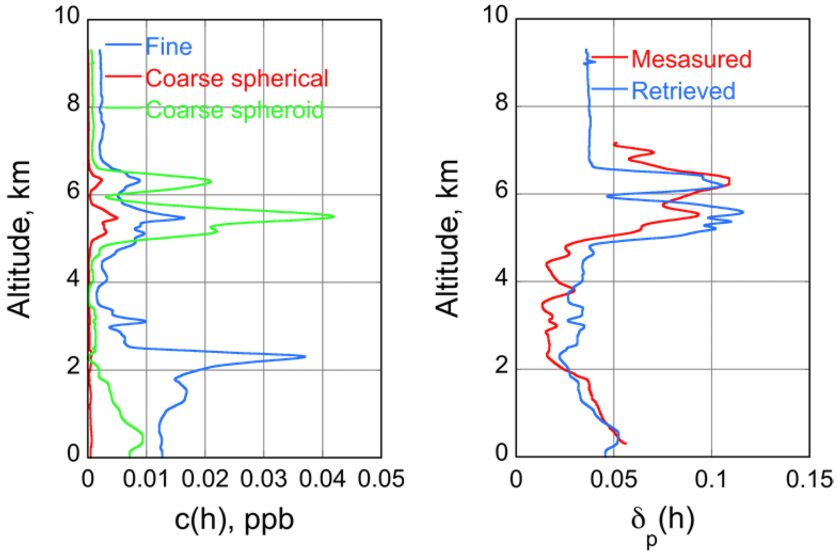

Figure 4. Retrieval of vertical profile of non-spherical (spheroids) particle concentration (left) and depolarization profile (right) at Minsk, 21 Apr 2010 15:50.

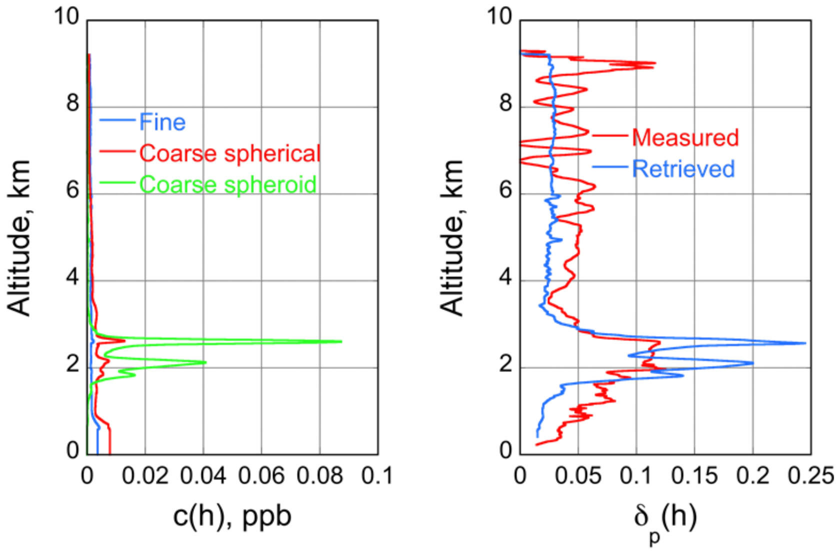

Figure 5. Retrieval of vertical profile of non-spherical (spheroids) particle concentration (left) and depolarization profile (right) at Lille, 19 May 2010 7:50.

References

Behrendt, A., Nakamura, T. Calculation of the calibration constant of polarization lidar and its dependency on atmospheric temperature. Opt. Express, 10, 805-817, 2002.

Chaykovskii A.P. Method for investigating the structure of the stratospheric aerosol layer based on laser echo depolarization measurements, Atmospheric and Oceanic Optics, V. 3, No.11, 1221-1223, 1990.

Dubovik, O. and King, M. A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements, Journal of Geophysical Research, 105, 20 673–20 696, 2000.

Dubovik, O., Holben, B. N., Lapyonok, T., Sinyuk, A., Mishchenko, M. I., Yang, P., and Slutsker, I. Non-spherical aerosol retrieval method employing light scattering by spheroids, Geophysical Research Letters, 29, DOI: 10.1029/2001GL014506, 2002.

Dubovik, O. Optimization of Numerical Inversion in Photopolarimetric Remote Sensing, in: Photopolarimetry in Remote Sensing, edited by Videen, G. nad Yatskiv, Y. and Mishchenko, M., 65–106, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2004.

Dubovik, O., Sinyuk, A., Lapyonok, T., Holben, B. N., Mishchenko, M., Yang, P., Eck, T. F., Volten, H., Munoz, O., Veihelmann, B., van der Zande, W. J., Leon, J.-F., Sorokin, M., and Slutsker, I. Application of spheroid models to account for aerosol particle non-sphericity in remote sensing of desert dust, Journal of Geophysical Research, 111, DOI:10.1029/2005JD006619, 2006.

Dubovik, O., Herman, M., Holdak, A., Lapyonok, T., Tanré, D., Deuzé, J.-L., Ducos, F., Sinyuk, A., and Lopatin, A. Statistically optimized inversion algorithm for enhanced retrieval of aerosol properties from spectral multi-angle polarimetric satellite observations, Atmospheric Measurement Techniques, 975–1018, 2011.

Müller, D., I. Veselovskii, A. Kolgotin, M. Tesche, A. Ansmann, and O. Dubovik. Vertical profiles of pure dust and mixed smoke–dust plumes inferred from inversion of multi-wavelength Raman/polarization lidar data and comparison to AERONET retrievals and *in situ* observations. Applied Optics, Vol. 52, Issue 14, 3178-3202, 2013.

Sassen, K. The Polarization Lidar Technique for Cloud Research: A Review and Current Assessment. *Bull. Amer. Meteor. Soc.*, **72**, 1848–1866, 1991.

Tarantola, A. Inverse Problem Theory: Methods for Data Fitting and Model Parameter Estimation, Elsevier, Amsterdam, 614 p., 1987.

Tsekeri, A., V. Amiridis, P. Kokkalis, S. Basart, A. Chaikovsky, O. Dubovik, R.E. Mamouri, A. Papayannis and J. M. Baldasano, Application of a Synergetic Lidar and Sunphotometer Algorithm for the Characterization of a Dust Event Over Athens, Greece, British Journal of Environment and Climate Change, DOI: 10.9734/BJECC/2013/2615, 2013.

Turchin, V.F., Kozlov, V.P., Malkevich, M.S. The use of mathematical-statistics methods in the solution of incorrectly posed problems, Sov. Phys. Usp. 13, 681–703, 1971.

Veselovskii, O. Dubovik, A. Kolgotin, T. Lapyonok, P. Di Girolamo, D. Summa, D. N.Whiteman, M. Mishchenko, and D. Tanre. Application of randomly oriented spheroids for retrieval of dust particle parameters from multiwavelength lidar measurements. J. Geophys. Res., 115(D21203), 2010.

Wagner, J., Ansmann, A., Wandinger, U., Seifert, P., Schwarz, A., Tesche, M., A. Chaikovsky, A., and Dubovik, O. Evaluation of the Lidar/Radiometer Inversion Code (LIRIC) to determine microphysical properties of volcanic and desert dust, Atmos. Meas. Tech., 6, 1707–1724, DOI: 10.5194/amt-6-1707-2013, 2013.

Young, A. T. Rayleigh scattering. Physics Today 35, 42–48, 1982.