WP5–NA5: Clouds and aerosol quality-controlled observations

Deliverable D5.8: Modified software for aerosol retrievals

Objectives

Task 5.2 of WP5 aims at the implementation of aerosol observations in Cloudnet (Illingworth et al., 2007). Key instruments for such purpose are the 3+2+1 EARLINET lidars, i.e., multiwavelength-depolarization-Raman lidars which deliver backscatter coefficients at three wavelengths, extinction coefficients at two wavelengths, and the depolarization ratio at one wavelength. For the implementation in Cloudnet, these instruments should be able to run continuously and unattended. The additional wavelengths provided by these instruments (see Fig. 1) are perfectly suited to analyze aerosol characteristics and to complete the observational features covered by the standard Cloudnet capabilities.

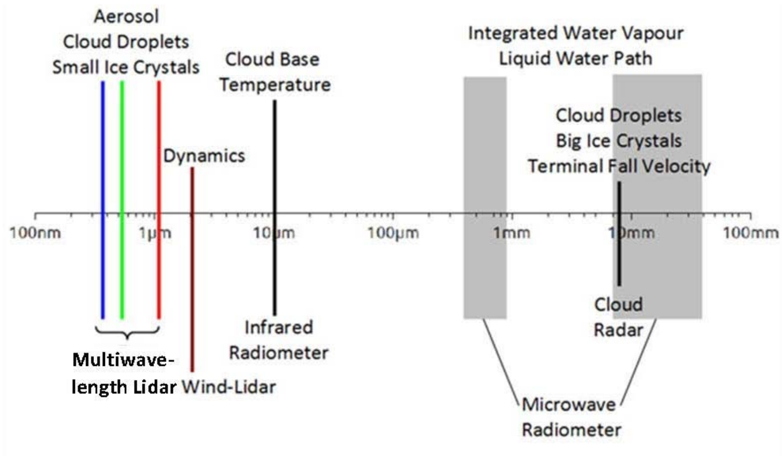

Fig. 1: Overview of wavelengths used by Cloudnet and EARLINET to characterize clouds, aerosols and meteorological parameters (Bühl, 2012). For the aerosol characterization, wavelengths in the visible range are best suited.

However, quality-controlled and calibrated lidar measurements require a number of methodical and instrumental efforts. In the following, the procedure for aerosol retrievals is described in terms of hard- and software for the example lidar PollyXT (Althausen et al., 2009, 2013) which is employed at TROPOS together with the standard Cloudnet instrumentation. PollyXT is a sophisticated, compact lidar to which the quality-assurance procedures proposed by EARLINET are applied. Without such high-quality measurements, a proper aerosol characterization as described in the following is not possible.

Calibration

In modern multiwavelength lidars a number of different receiving channels are installed to make use of as much information from the atmosphere as possible (elastic and Raman scattering, change in polarization state due to scattering, etc.). In this way, high-quality aerosol properties are obtained on a vertically resolved basis. However, because of the high background noise, Raman lidar observations during daytime are challenging. Therefore, for continuous (24/7) measurements, we concentrate on the use of channels for elastic backscattering, including depolarization. The key challenge to succeed with automated aerosol retrievals is the calibration of those channels.

1) Calibration of backscatter

The backscatter signal strength *P* for a certain height/range *R* at the wavelength λ can be described for each channel by:

$$P(R,\lambda)=\frac{C(R,\lambda)}{R^2}\left[\beta_{\mathrm{par}}^{\lambda}(R)+\beta_{\mathrm{mol}}^{\lambda}(R)\right]\exp\left\{-2\int_0^R\left[\alpha_{\mathrm{par}}^{\lambda}(r)+\alpha_{\mathrm{mol}}^{\lambda}(r)\right]\mathrm{d}r\right\}, \qquad \text{Eq. (1)}$$

with the lidar calibration constant *C* containing all instrument-relevant quantities, the sum of the molecular and particle backscatter coefficient β, and the atmospheric transmissivity described by the molecular and particle extinction coefficient α. The molecular backscatter and extinction coefficients can easily be calculated for pressure and temperature profiles obtained from radio soundings or model output with well-known scattering formulas (Bucholtz, 1995). To obtain atmospheric quantities from the received power *P,* the lidar calibration constant needs to be known. For usual lidar applications, the particle backscatter coefficient is obtained by applying the Raman (Ansmann, 1990) or Klett-Fernald method (Klett, 1981; Fernald, 1984) to the received signals. With these methods, the lidar signal is calibrated in a certain height range of the atmosphere for which only molecular scattering is assumed. However, these methods have to be applied carefully and a temporal averaging over at least 30 minutes is needed to increase the signal-to-noise ratio (SNR) in the calibration height region. Thus, for temporally high-resolved 24/7 aerosol analysis, these methods are not ideal.

For that reason, an absolute calibration is performed by calculating the lidar calibration constant *C* sporadically from either the molecular calibration as described before or from the calibration of the vertically integrated extinction coefficient (derived by assuming a constant extinction-to-backscatter ratio) to AERONET optical depth. An example of the variability of this lidar constant for the three emitted wavelengths of PollyXT is shown in Fig 2.

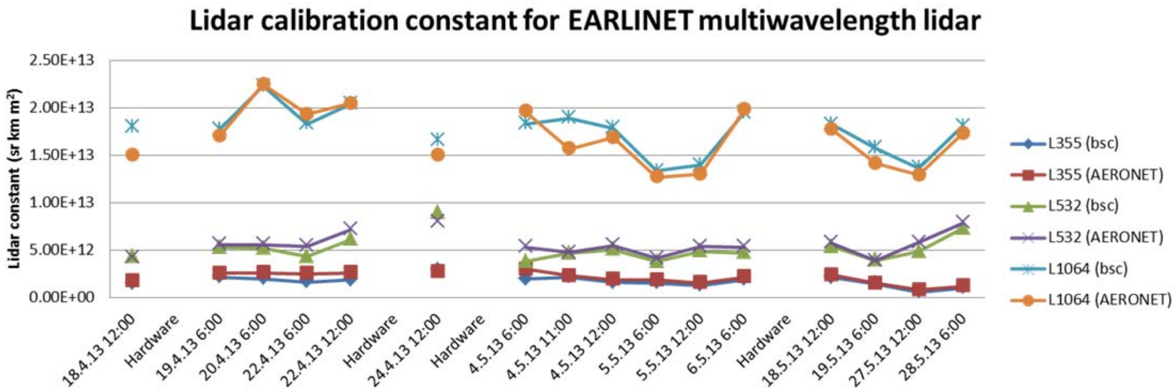

Fig. 2: Temporal evolution of the lidar calibration constant for 355, 532, and 1064 nm as obtained by two different methods (AERONET and backscatter=bsc) for the EARLINET lidar PollyXT.

During the six weeks of measurements in spring 2013 shown in Fig. 2, no technical changes at the lidar were performed in order to obtain stable and comparable signals. As can be seen, both methods agree well and also the stability of the lidar constant is reasonable for the case of PollyXT. A maximum variation of the lidar calibration constant of about 50% was observed, which is nevertheless still good enough for an aerosol characterization in 24/7 mode. It is worth mentioning that the stability of the lidar calibration constant depends on many technical issues like laser power, receiver sensibility etc. Usually, the calibration constant can change by some orders of magnitude depending on the purpose of observation or the stability of the instrument.

Since the molecular backscatter and extinction coefficients can be calculated from temperature and pressure profiles and the lidar calibration constant can be estimated as described above, the quasi particle backscatter coefficient can be calculated by neglecting the particle extinction in Eq. (1) with an error of much less than 50%:

$$\beta_{\mathrm{par}}^{\lambda}(R) \approx \frac{P(R,\lambda)R^2}{C(\lambda)} \exp\left\{2\int_0^R \left[\alpha_{\mathrm{mol}}^{\lambda}(r)\right]\mathrm{d}r\right\} - \beta_{\mathrm{mol}}^{\lambda}(R) = {}^{\mathrm{quasi}}\beta_{\mathrm{par}}^{\lambda}(R). \qquad \text{Eq. (2)}$$

The calibrated quasi particle backscatter coefficient at three wavelengths is then used as the input for the particle characterization described below.

Other methods to be investigated in future would be to use real backscatter profiles as obtained with the Raman and Klett methods by automatizing the atmospheric calibration of the lidar signals. Such efforts are currently investigated within WP2 for the EARLINET Single Calculus Chain (Baars, 2012, 2013; D'Amico, 2012), see below. Then, the atmospheric calibration at a low temporal resolution could be used as a basis for high-resolution aerosol characterization.

2) Calibration of depolarization ratio

The calibration of the depolarization measurements of PollyXT is done with the so-called Δ90°-method (Freudenthaler, 2009) in agreement with EARLINET standards. For this purpose, a motorized filter wheel is implemented in the receiver unit of PollyXT to perform the Δ90°-calibration automatically three times a day. With known transmission ratios *D* of the receiver optics concerning polarization a calibration constant *V** can be calculated from which the volume depolarization ratio is derived without any further assumptions:

$$\delta_{\mathrm{vol}}(R) = \frac{1 - \frac{\delta(R)}{V^*}}{\frac{\delta(R)}{V^*}D_{\mathrm{tot}} - D_{\mathrm{cr}}}, \qquad \text{with } \delta = \frac{P_{\mathrm{cr}}}{P_{\mathrm{tot}}}. \qquad \text{Eq. (3)}$$

P_{cr} and P_{tot} are the cross-polarized and total signals, respectively.

Aerosol characterization

With the calibration methods described above, aerosol characterization can be done by means of (quasi) backscatter coefficients and depolarization ratio. From the (quasi) backscatter coefficients, the intensive aerosol quantity of the (quasi) Ångström exponent,

$${}^{\mathrm{(quasi)}}\mathring{a}_{\lambda_1/\lambda_2} = -\ln\left(\frac{{}^{\mathrm{(quasi)}}\beta_{\mathrm{par}}^{\lambda_1}}{{}^{\mathrm{(quasi)}}\beta_{\mathrm{par}}^{\lambda_2}}\right) \Big/ \ln\left(\frac{\lambda_1}{\lambda_2}\right),$$

is calculated to obtain information on particle size.

The (quasi) particle depolarization ratio,

$${}^{\mathrm{(quasi)}}\delta_{\mathrm{par}}^{\lambda}(R) = \left[\delta_{\mathrm{vol}}^{\lambda}(R) + 1\right]\left(\frac{\beta_{\mathrm{mol}}^{\lambda}(R)\left[\delta_{\mathrm{mol}}^{\lambda} - \delta_{\mathrm{vol}}^{\lambda}(R)\right]}{{}^{\mathrm{(quasi)}}\beta_{\mathrm{par}}^{\lambda}(R)\left[1 + \delta_{\mathrm{mol}}^{\lambda}\right]} + 1\right)^{-1} - 1, \qquad \text{Eq. (4)}$$

also an intensive property, is calculated from the (quasi) backscatter coefficient and volume depolarization ratio profiles to get information about the particle shape.

Thus, finally four extensive properties and four intensive properties are available for aerosol characterization as can be seen in Fig. 3.

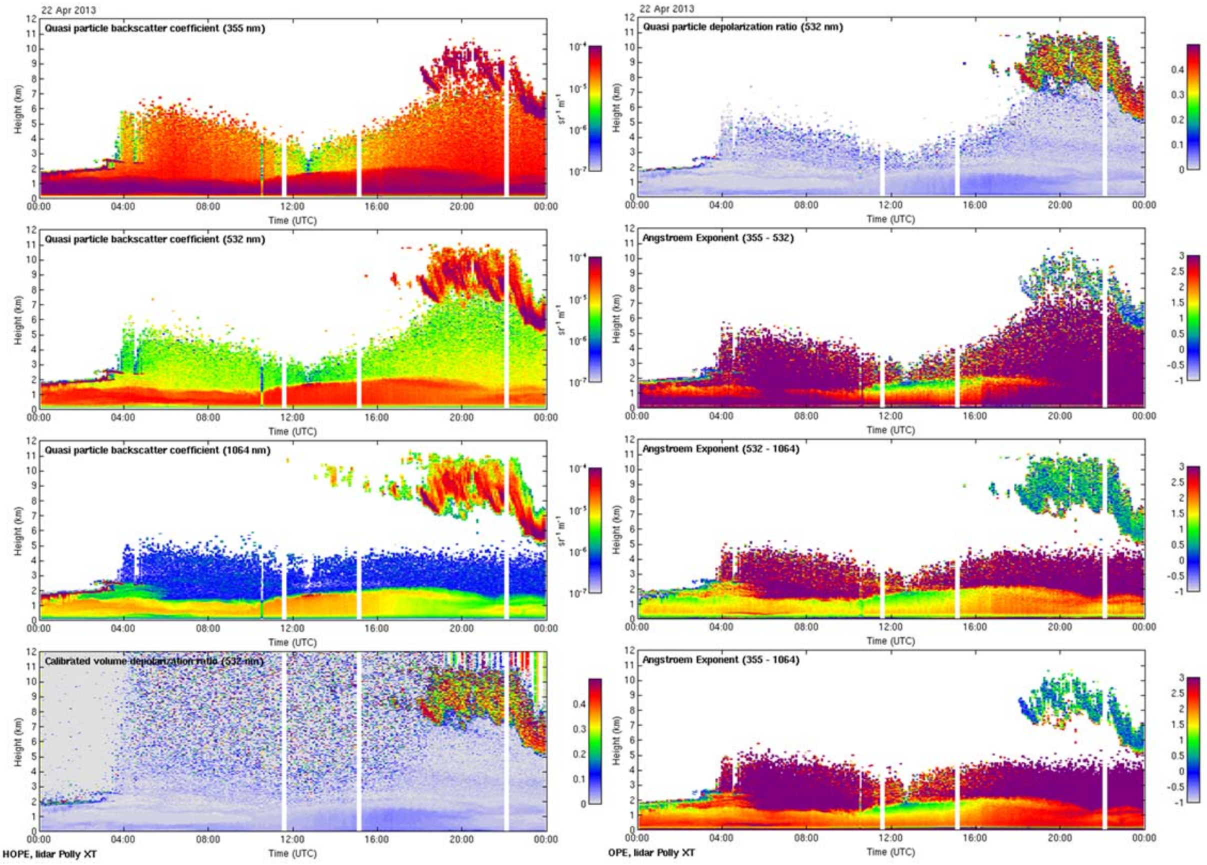

Fig. 3: Quantities obtained from the automatic lidar PollyXT in 24/7 mode. Left panels show the extensive properties and right panels the intensive properties. Three times a day the automatic depolarization calibration takes place indicated by the three white vertical bars.

Beside the fact that these quantities are already sufficient to characterize aerosol, an attempt is made to categorize the aerosol concerning different types in analogy to the Cloudnet classification. For this purpose, two options are available at the moment, a less specific lidar-1 classification and a more specific lidar-2 classification. For these classifications, the backscatter profiles are used to detect aerosol and cloud layers and distinguish between those two. Simple thresholds are used to separate liquid clouds from other features like aerosol and ice clouds. Because droplets have a very high backscatter intensity, this method is well suited for the discrimination and no errors in the sense of false classifications are expected. For aerosol and ice clouds, the classification is much more sophisticated. Here, the intensive particle properties are used for the categorization based on long-term observations within EARLINET and other projects. The principle of typing is shown in Fig. 4.

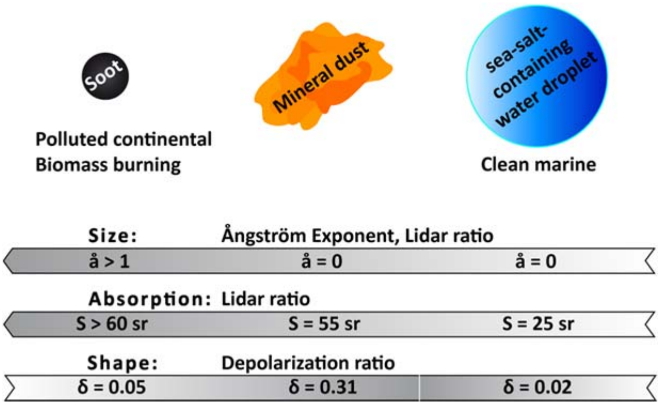

Fig. 4: Schematic illustration how different aerosol types could be classified by means of Ångström exponent, lidar ratio, and depolarization ratio (Tesche, 2011).

The complete typing procedure based on the backscatter, depolarization, and Ångström profiles is illustrated in Fig. 5.

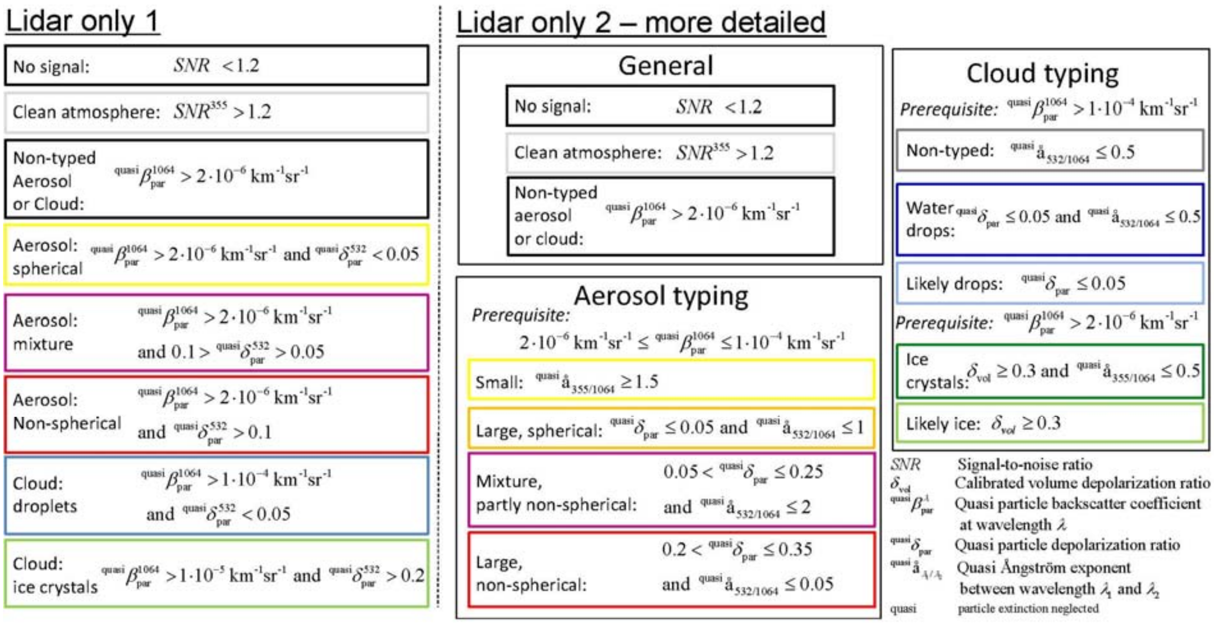

Fig. 5: Overview of classification scheme for aerosols and clouds as performed with the EARLINET lidar PollyXT. Two different schemes are presented.

As can be seen, the lidar-only-1 classification consists of six particle classes: non-typed particles or clouds, spherical aerosol, aerosol mixture, non-spherical aerosol, ice clouds, and liquid clouds. The "clean atmosphere" class represents a Rayleigh atmosphere where pure molecular scattering can be assumed. The more sophisticated lidar-only-2 scheme makes use of all available parameters and can be used for a more detailed and probabilistic classification. For example, if all parameters are available, ice crystals are clearly identified. However, if only depolarization information is available, the category "likely ice" is chosen, because no information is available on size in terms of the Ångström exponent. Finally, four aerosol classes and five cloud classes are available at the moment, but of course the definition is still under discussion and subject to change.

Example for aerosol categorization

Fig. 6 shows the classification schemes of Cloudnet and PollyXT for an example day in April 2013.

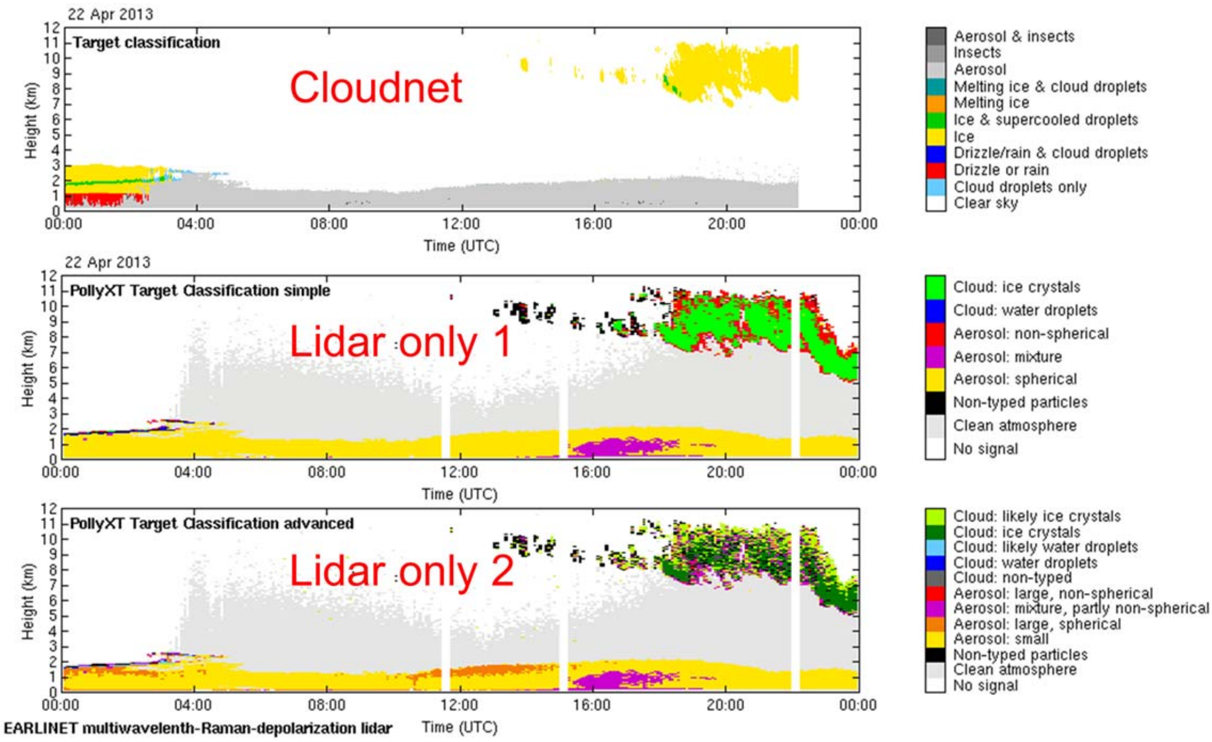

Fig. 6: Top: Cloudnet target classification (Hogan and O'Connor, 2004). Center and Bottom: Two different target classifications (following Fig. 5) as obtained from the multiwavelength-Raman-depolarization lidar PollyXT.

The standard Cloudnet classification (Hogan and O'Connor, 2004) is able to distinguish between the different cloud types and to detect aerosol. However, no discrimination between aerosol types is possible. Also, a wrong classification is found between 0 and ca. 3 UTC for the cloud and precipitation objects below 2 km. At around 2 km, clearly a melting layer is observed and only liquid droplets are expected below that height. However, because of the current Cloudnet classification, it is partly falsely classified as falling ice.

In comparison, the lidar-only classifications show similar features. The cirrus cloud above 8 km height in the afternoon and evening is mostly well identified, even if some small features are only classified as "non-typed". The reason for that is the lack of information from all wavelengths, because the short wavelengths are not sensible enough for such thin clouds in this height range. The aerosol layer (planetary boundary layer) below 2 km is well detected and a distinction between spherical aerosol particles and a mixture of aerosol, probably polluted dust, could be made for the lidar-1 classification on the basis of depolarization. In the lidar-2 classification, even the hygroscopic growth of the aerosol particles with height is well observed and classified in the daytime convective boundary layer (see between 1.5 and 2 km from 11 to 16 UTC). Due to the growth of the aerosol particles the Ångström exponents get lower and the aerosol is classified as consisting of large particles.

During the night between 0 and 3 UTC, when Cloudnet had problems with the classification, the lidar can detect the base of the cloud only, and both lidar algorithms classified this base as liquid or non-typed. Below the cloud base, the lidar is not sensitive to observe drops as Cloudnet does, and only aerosol is categorized. This means that most probably only a few big drops were present to which only the radar was sensitive. This also shows the high potential of the synergy when combining both categorization schemes.

Integration of lidar aerosol typing in Cloudnet

As can be concluded from the discussion above, the biggest benefit could be gathered, if the Cloudnet classification scheme and the lidar classification scheme are combined. Then, eight lidar quantities are available in addition to the already existing Cloudnet quantities for an advanced categorization of both aerosol and clouds. In this way, errors, i.e. misclassifications, could be minimized and a detailed data set could be provided at European Supersites hosting both Cloudnet standard equipment and reliable, automatic, high-quality lidars based on EARLINET standards.

Integration of EARLINET algorithms in Cloudnet

In the next step, EARLINET algorithms developed within WP2 can be directly integrated in a combined Cloudnet/EARLINET station. After cloud screening (by making use of the classification schemes described above), 30-min average profiles of the 24/7 continuous lidar measurements can be calculated and directly used as input to the Single Calculus Chain (SCC) developed within EARLINET (Baars, 2012; D'Amico, 2012, 2014a). The advantage of the SCC is that the raw signals of different instruments are harmonized (similar to Cloudnet, D'Amico, 2014b) and the full palette of optical properties is calculated (Mattis, 2014) together with its errors (Amodeo, 2014) with state-of-the-art algorithms. The output products go directly into the ACTRIS/EARLINET database. A full documentation of this methodology is currently prepared for a special issue on EARLINET in Atmospheric Measurement Techniques (AMT). Examples of such optical profiles from the EARLI09 campaign at Leipzig, in which also PollyXT took part, is shown in Fig. 7.

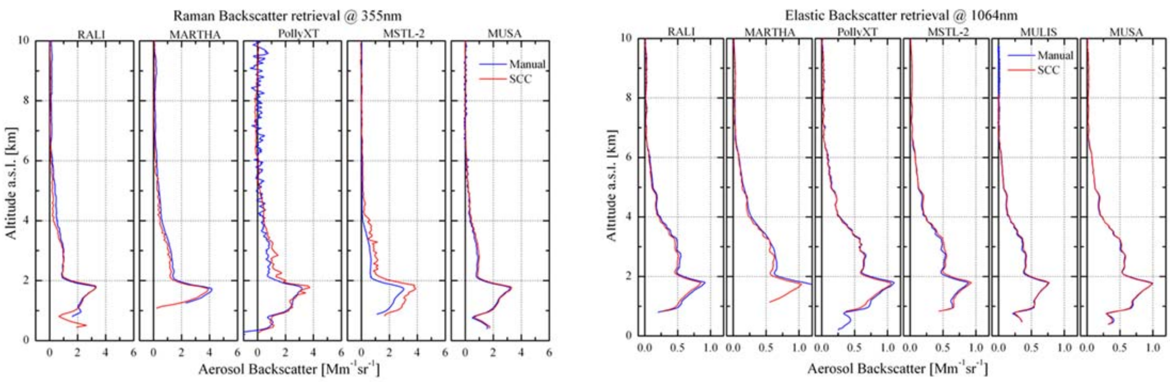

Fig. 7: Vertical profiles of backscatter coefficient at 355 and 1064 nm as obtained for five different lidar systems during EARLI09 in Leipzig. Blue lines show the manual analysis done by the operating group; red lines show the output of the Single Calculus Chain.

Here, the backscatter coefficient determined with the Raman method for 355 and 1064 nm is shown for the SCC and the user's manual analysis. A very good agreement within the accepted error range is obtained from this comparison for all EARLINET lidar systems, which shows the high-quality performance of this software package and the potential for routine application at EARLINET stations as well as at combined, continuously operating EARLINET/Cloudnet stations.

Conclusion

Aerosol characterization with automated, high-quality EARLINET-type lidars in Cloudnet is possible with both a high-temporal-resolution 24/7 mode for aerosol categorization and a low-temporal-resolution mode that provides high-quality data products with errors following the standards of the EARLINET database. The integration of EARLINET and Cloudnet is ongoing and offers a high potential for future synergistic profiling of aerosols, clouds and their interaction by combining modern state-of-the art atmospheric instruments.

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