Deliverable D2.14: Implementation of common EARLINET/Cloudnet algorithms and products

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Work package no	**WP2**
Deliverable no.	**D*2.14***
Lead beneficiary	**TROPOS**
Deliverable type	☑ R (Document, report) ☐ DEC (Websites, patent fillings, videos, etc.) ☐ OTHER: please specify ....
Dissemination level	☑ PU (public) ☐ CO (confidential, only for members of the Consortium, incl Commission)
Estimated delivery date	**Month 46**
Actual delivery date	***28/02/2019***
Version	**V1**
Comments	

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Task 2.3 in WP2 of ACTRIS-2 has aimed at the synergy between EARLINET and Cloudnet. It has been driven by the increasing scientific interest in combined aerosol and cloud observations to study aerosol-cloud interactions. The task has been led by TROPOS, and CNR, CNRS, NOA, FMI, INOE, KNMI, TUD, RIUUK, DWD, UREAD, STFC, CNISM and NUIG have contributed to the developments.

Task 2.3. had three main goals concerning instrument synergy:

- Implementation of Doppler lidars at selected Cloudnet and EARLINET sites,
- Implementation of multi-wavelength/polarization lidars at Cloudnet sites,
- Implementation of water-vapour Raman lidars at selected Cloudnet and EARLINET sites,

which had to be accompanied by the development of common data products and processing chains as well as by the optimization of observing strategies, standardization and quality assessment.

First of all, the Cloudnet workflow has been updated to accomplish Doppler wind lidar processing and linking with EARLINET aerosol lidar processing (ACTRIS aerosol remote sensing DC).

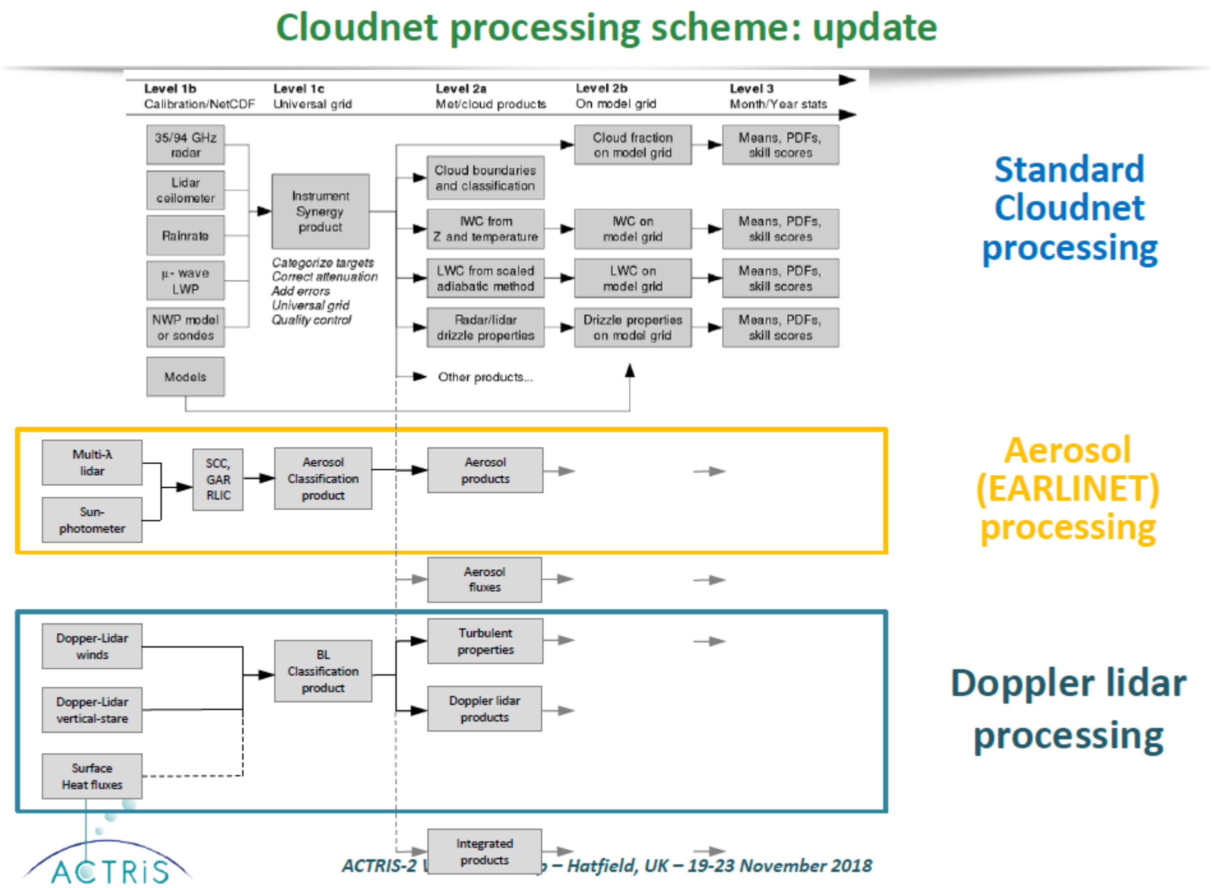

Figure 1. Updated Cloudnet processing scheme including Doppler wind lidar processing and link with ACTRIS aerosol profiling.

Figure 1 shows the updated processing scheme as presented in D2.2 and at the final ACTRIS WP-2 workshop in Hatfield, UK. As a further step, also unified atmospheric model data have been made available and harmonized within EARLINET and Cloudnet, so that the same model data is used in the

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Cloudnet and EARLINET processing schemes. In the following, the achieved developments concerning the implementation of common algorithms and products are reported.

- Implementation of Doppler lidars at selected Cloudnet and EARLINET sites:

The number of available Doppler lidars at ACTRIS sites has steadily increased during the time of ACTRIS-2 and Doppler lidars are meanwhile available at several ACTRIS (EARLINET and Cloudnet) sites. HALO Photonics Doppler lidars have been operated at Leipzig (TROPOS), Punta Arenas (TROPOS), Lindenberg (DWD), Chilbolton (UREAD, STFC), Hyytiälä (FMI), Limassol (TROPOS), Finokalia (FMI), Kosetice (FMI), Jülich (RIUUK), Sodankylä (FMI), Vehmäsmaki (Kuopio, FMI), Potenza (CNR) and Granada (UGR). Leosphere wind lidars are available at Mace Head (NUIG) and Palaiseau (CNRS).

A new methodology for the post-processing of the background noise was developed for HALO Photonics wind lidar systems to improve sensitivity and to obtain reliable characterization of the uncertainty.

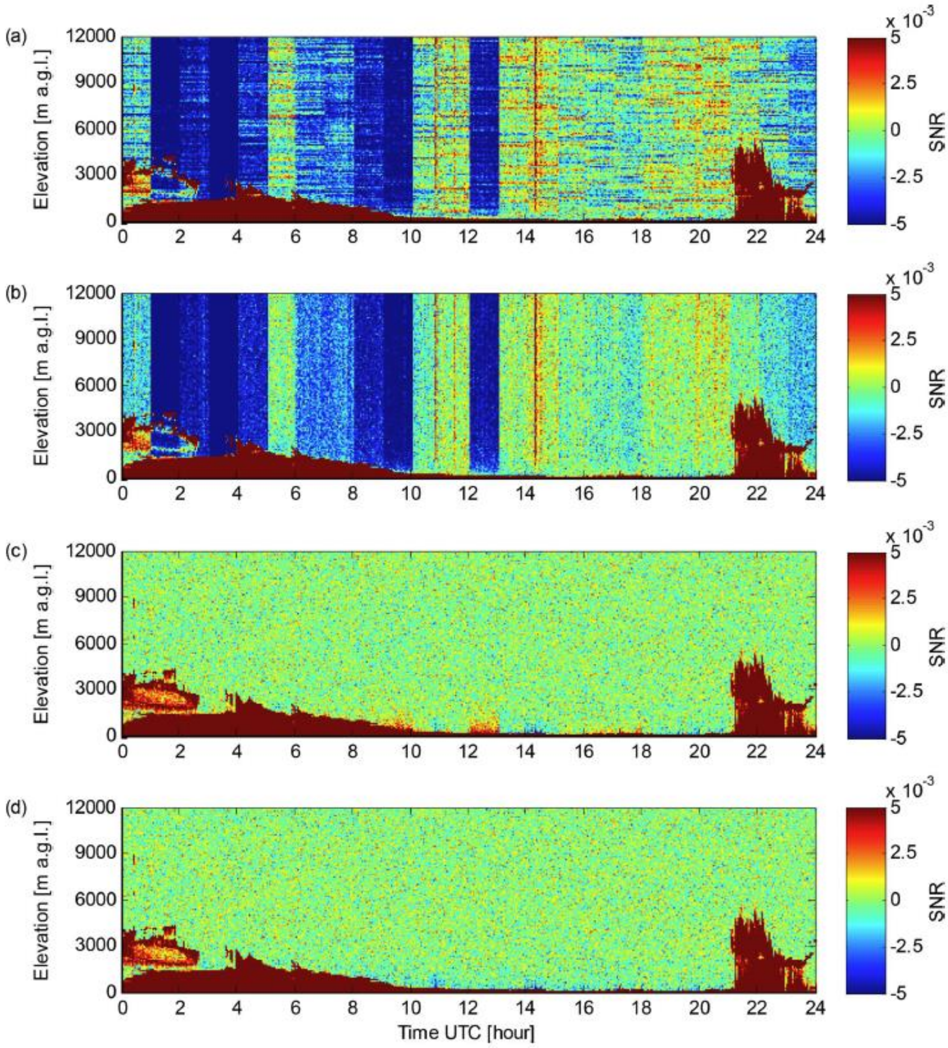

Figure 2. Example time series of HALO Doppler wind lidar signal-to-noise ratio observed at Helsinki on 6 May 2018 illustrating the improvement of the signal quality by applying several post-processing steps (from (a) to (d), Vakkari et al., 2019).

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This development led to a significantly increased signal-to-noise ratio (SNR) by applying a sophisticated background subtraction technique as shown in Fig. 2 for a Doppler lidar observation at Helsinki, Finland. The top panel shows the measured signal (SNR) as provided by the manufacturer to the user/data provider while the bottom panel shows the result signal after several post-processing steps.

The development activities resulted in a scientific publication describing the novel post-processing algorithm for Halo Doppler lidars and uncertainty characterizations (Vakkari et al., 2019). Furthermore, the analysis concerning the noise of the Doppler lidars showed that even if the technical specifications of two Doppler lidar systems are identical, their instrumental noise characteristics can be quite different. Therefore, it was recommended that the lidar operators should inspect each system individually to ensure the highest data quality. For that purpose, a tool box has been provided via GitHUB (Manninen, 2019) to use the newly developed post-processing methodologies at other ACTRIS sites allowing for harmonized products.

Furthermore, the potential of obtaining quantitative information on the particle backscatter coefficient from Doppler lidars for synergistic use in Cloudnet retrievals have been analysed and compared to ACTRIS high-power lidars. Also for this purpose the signal quality has significantly improved as shown in Fig. 3 c and d.

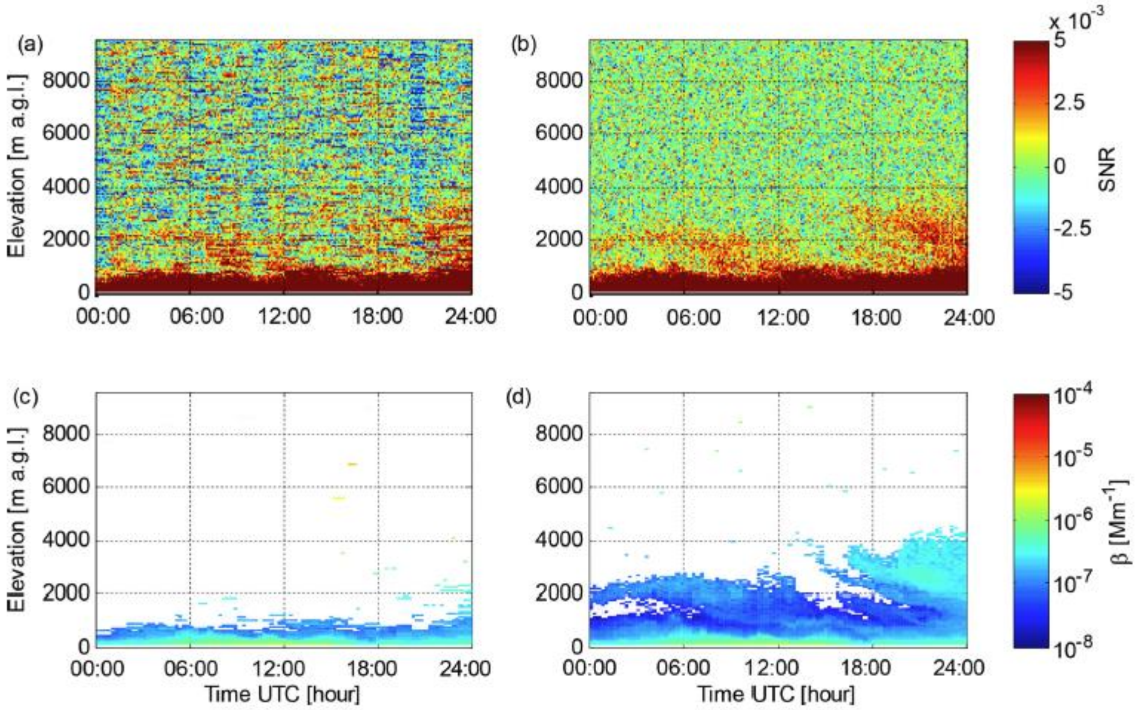

Figure 3. Data from HALO wind lidar at Finokalia on 8 July 2014. Time series of the SNR profile (a) without post-processing and (b) after post-processing. Time series of attenuated backscatter coefficient obtained with 350 s integration time and (c) without post-processing and (d) with post-processing.

The comparison to the ACTRIS high-power aerosol lidar PollyXT at Finokalia is shown in Fig. 4. Considering the wavelength difference (1064 nm for PollyXT, 1500 nm for HALO), the agreement between the two systems is reasonably good. This result had led to the conclusion, that the Doppler wind lidars of HALO Photonics have the potential to be also used for aerosol retrievals.

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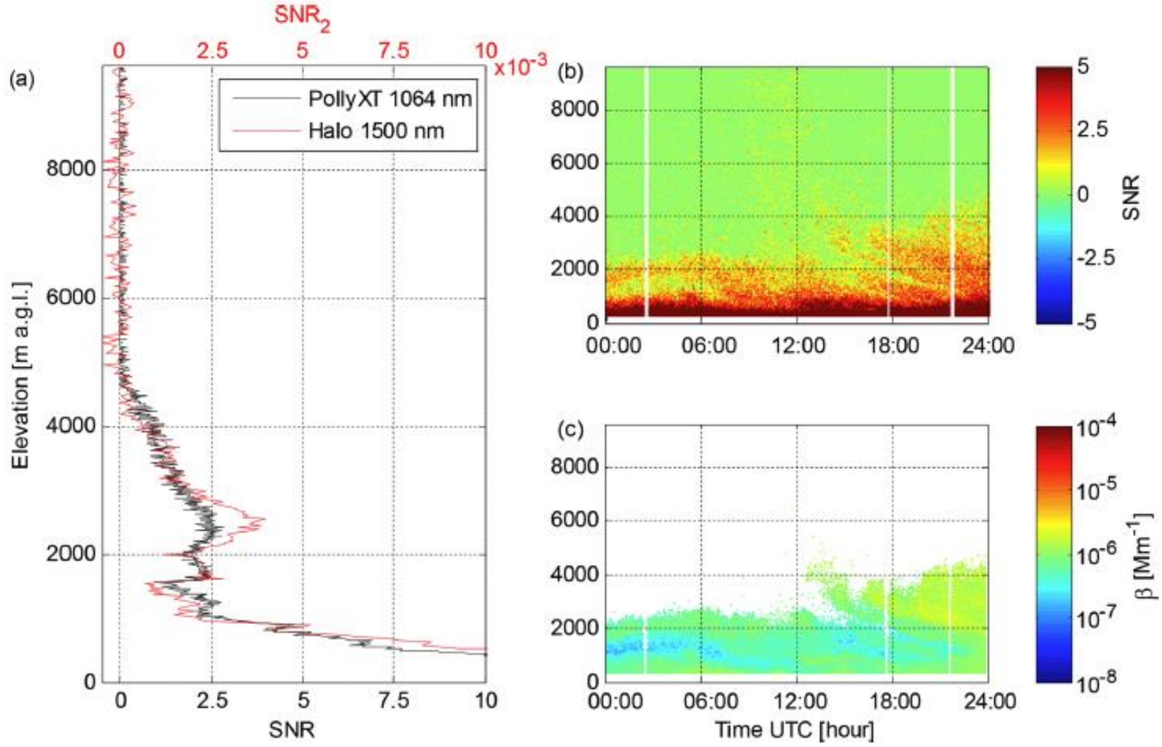

Figure 4: Comparison of Halo Doppler aerosol profiles to ACTRIS high-power lidar PollyXT at Finokalia. (a) Vertical profiles of SNR from PollyXT at 1064 nm wavelength and post-processed SNR of HALO, (b) time series of PollyXT SNR at 1064 nm wavelength and (c) time series of PollyXT attenuated backscatter at 1064 nm wavelength with 360 s integration time at Finokalia on 8 July 2014 for comparison with the results presented in Fig. 3.

Observation strategies and recommendations have been developed (VAD technique, Päschke et al., 2015) to also obtain reliable information on horizontal wind speed while not losing too much information on the vertical air motions. Fig. 5 presents some of the potential products from the HALO instrument for an example observation at Limassol, Cyprus.

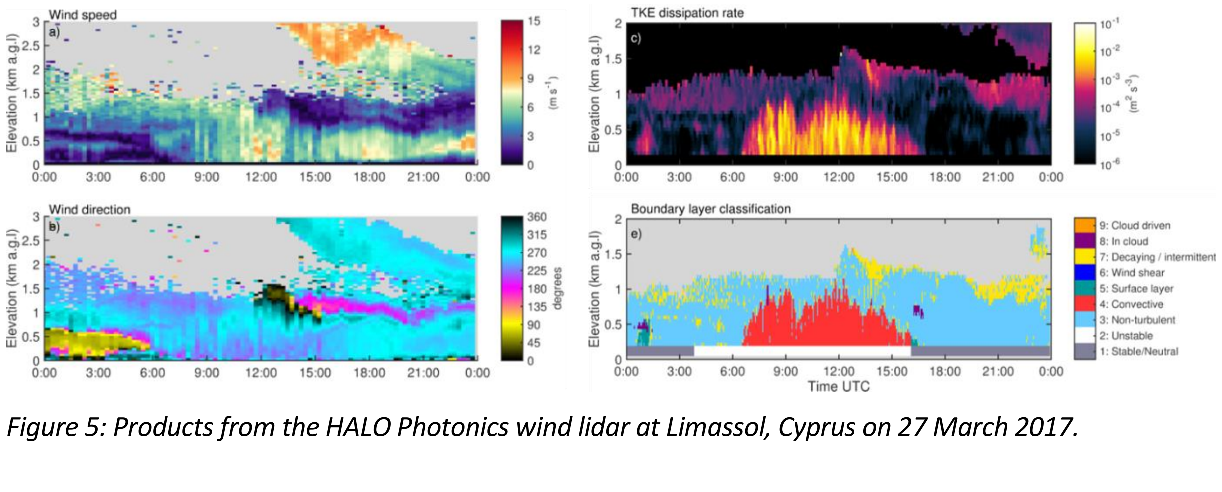

Figure 5: Products from the HALO Photonics wind lidar at Limassol, Cyprus on 27 March 2017.

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In the top left panel, the obtained total horizontal wind speed is shown, while in the lower left panel the corresponding wind direction is presented. From the high-resolution wind vector (including vertical motion), the turbulent kinetic energy dissipation rate is derived as shown in the upper right panel. Bringing all information together, the atmospheric boundary layer can be classified according to dynamic situation as plotted in the lower right panel. A respective scientific article have been published (Manninen et al., 2018) describing the identification tree for PBL classification based on the development to improve and characterize the wind lidar signal as introduced above.

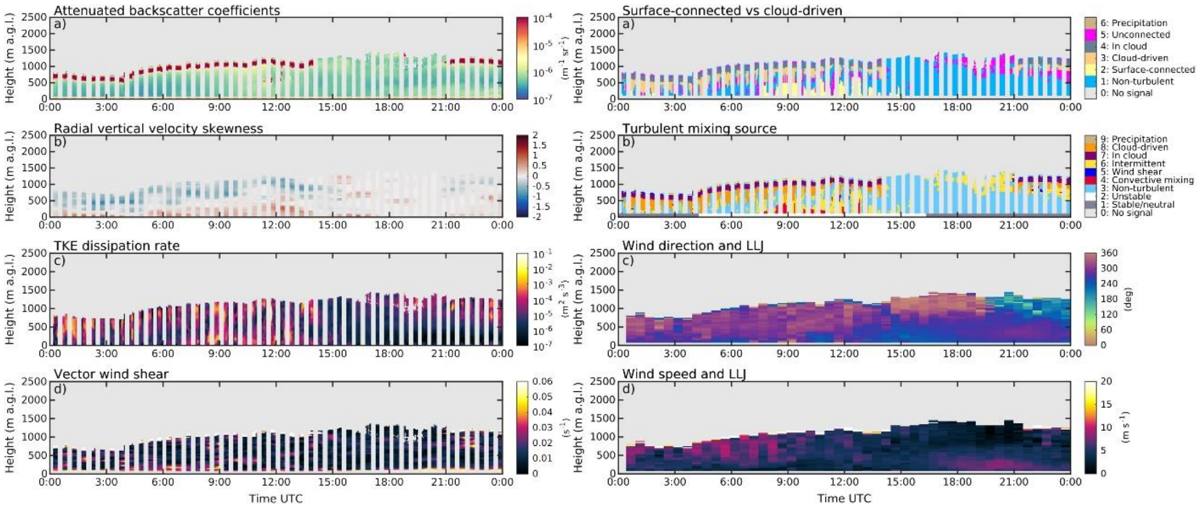

Figure 6: Wind observations at Hyytiälä, Finland, on 22 September 2016.

Figure 6 presents another example measurement with Doppler lidar but from Hyytiälä Finland. On the left, time-height plots of (a) attenuated backscatter coefficient, β, (b) vertical velocity skewness, (c) TKE (turbulent kinetic energy) dissipation rate, ε, and (d) vector wind shear, calculated from Doppler lidar measurements are shown. Vertical grey lines indicate periods when the Doppler lidar was scanning. On the right, time-height plots of PBL classification showing (a) connection with the surface (i.e., surface driven versus cloud driven) and (b) the turbulent mixing source, together with time-height plots of (c) wind direction and (d) wind speed are presented. The products from the wind lidar presented in, e.g., Fig. 6 shows that using the backscatter information and the turbulence information from the Doppler lidar, a classification of the PBL according to cloud-driven, in-cloud, surface-connected or non-turbulent can be made.

The developed algorithms have been applied on long-term data sets at Jülich, Germany and Hyytiälä, Finland, showing its capability to be used for long-term EARLINET/Cloudnet data sets and to derive climatology of turbulence and wind characteristics, which is a prerequisite for aerosol-cloud interaction studies.

Summarizing, harmonised consistent retrievals and measurement strategies have been devolved together with standard operating procedures providing the following additional wind products in high temporal resolution including uncertainties:

- Horizontal wind profiles in the PBL
- Turbulent properties
- BL description together with source of turbulence

- Implementation of multi-wavelength/polarization lidars at Cloudnet sites:

A growing number of ACTRIS stations with collocation of Cloudnet instruments and sophisticated multiwavelength/polarization lidars (high-power lidars) allow for new research possibilities by using synergistic information of those two ACTRIS components. Combined Cloudnet/EARLINET measurements have been made during ACTRIS-2 at Leipzig (TROPOS), Cabauw (KNMI, TUD), Palaiseau (CNRS), Potenza (CNR), Granada (UGR), Limassol (TROPOS), Finokalia (NOA, CNR, FMI) and Punta Arenas (TROPOS).

The exploitation of the potentials requires the linkage of multiwavelength/polarization lidars with the Cloudnet processing. As a first prerequisite, a new version of the EARLINET Single Calculus Chain (SCC, D'Amico et al., 2015) has been implemented allowing the production of high-resolution pre-processed lidar signals in a common format for any type of lidar (see D2.8 - Implementation of the lidar quicklook database). Based on this achievement, retrievals for a particle-like backscatter coefficient, the calibrated attenuated backscatter, and the depolarization ratio, have been developed as Cloudnet requires quantitative products in temporal high resolution. Finally, a stand-alone lidar-based target categorization in analogy to the Cloudnet target categorization could be finalized (Baars et al., 2017).

While in the beginning, the necessary lidar calibration constant had to be calculated offline, meanwhile an automatic calibration procedure using the SCC-retrieved particle backscatter and extinction coefficients have been implemented together with an improved error characterization (see Task WP2.1). As an example, SCC-derived lidar constant for the high-power lidar at Hohenpeißenberg, RALPH, are shown in Fig. 7. Here the lidar constant for 532 nm as obtained from the elastic aerosol retrieval only and by using Raman channels is shown. A good agreement between the different methodologies implemented in the SCC is found.

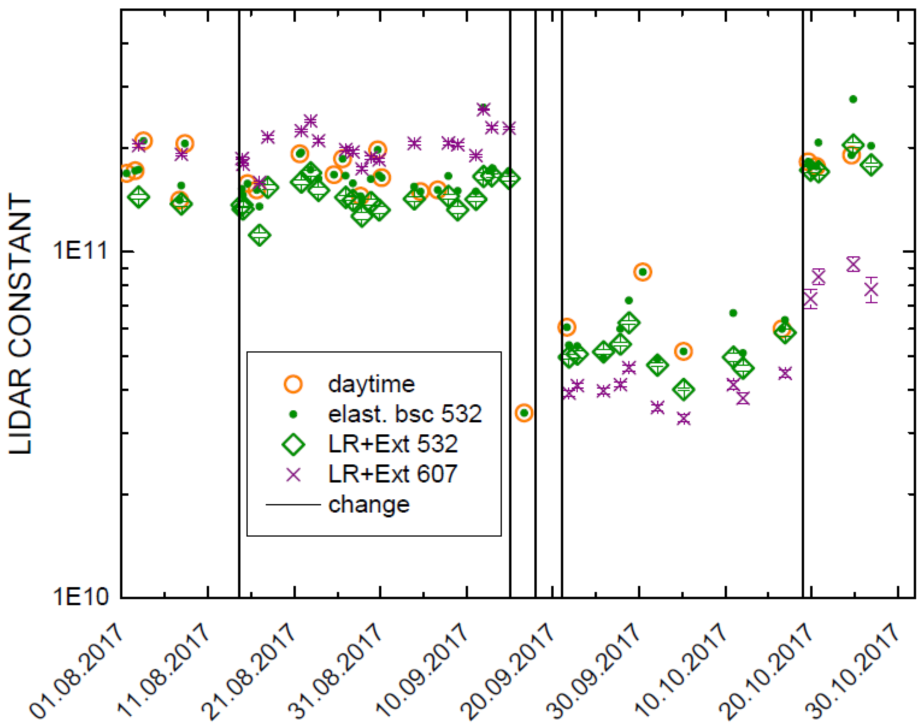

Figure 7: Time series of the obtained lidar constant for the high-power lidar RALPH at 532 nm using different methodologies. Black vertical lines indicate changes in the system setup.

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This is a big step forward toward synergistic retrievals by making use of high-power lidars and Cloudnet instruments, as the SCC now also provides the possibilities to calculate the lidar calibration constant for all different lidar types. As an example, quantitative high-resolution products for the lidar system operated in Potenza are shown in Fig. 8.

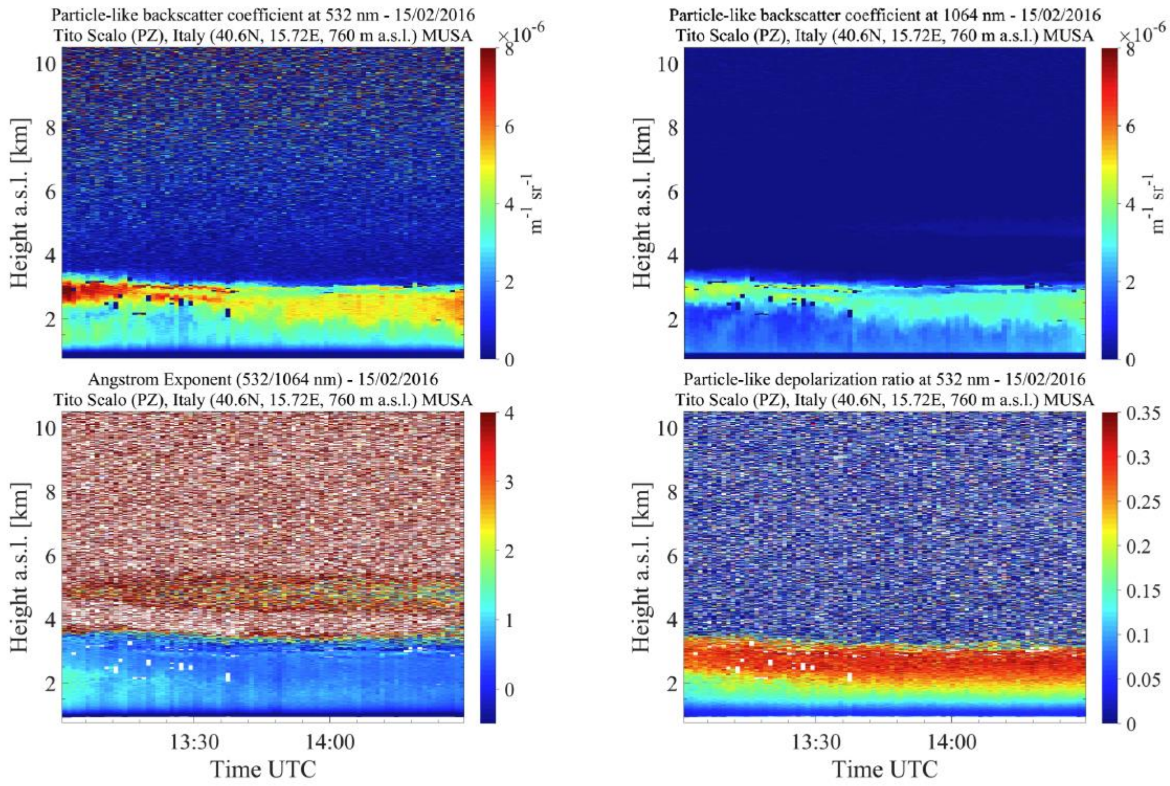

Figure 8. EARLINET high-resolution aerosol products for Potenza on 15 February 2016.

Such products can have many potential applications. One example is the Early Warning product aiming to alert for aviation hazards related to desert dust or ash presence realized into the EUNADICS-AV H2020 project (Papagiannopoulus et al., 2018). In addition, thanks to the combination with Cloudnet information, these products are a perfect basis for aerosol-cloud interaction studies.

Long-term investigations with PollyXT lidar systems (Baars et al., 2016) have shown that for continuously running lidar systems, the calibration constant stays relatively stable unless systems changes are performed (Fig. 9, first tree panels). It is also obvious that the retrieved parameter can also be used to monitor the instrument performance.

Furthermore, it was shown that the methodology proposed by Freudenthaler, 2016, in the framework of WP2.1 to calibrate polarization-sensitive lidar systems can be successfully implemented in the routine measurements of continuously operating systems (Engelmann et al., 2016). Fig. 9 shows as well (see values for V* at 355 nm and 532 nm, last 2 panels) that except for specific changes in the lidar system setup (namely neutral density filter change only) also this calibration factor is temporally stable. Thus, also this factor can be used as an indicator of lidar performance. Furthermore, it proofs that reliable high-resolution products as needed for Cloudnet are possible from high-power aerosol lidars. This

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methodology has been successfully implemented in the SCC so that every lidar type (commercial/home made) can be processed now.

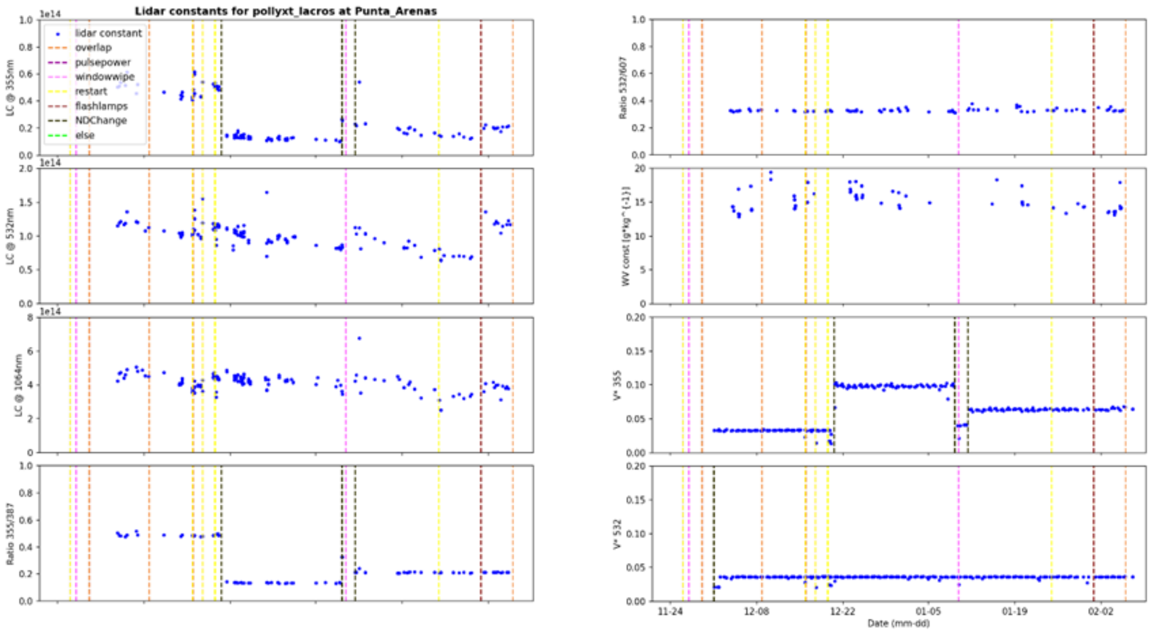

Figure 9. Lidar constants, depolarization calibration factors (V) and water-vapour calibration parameter for PollyXT at Punta Arenas, Chile. Vertical lines indicate changes in the lidar system as described in the legend.*

Continuous 24/7 measurements of polarization/multiwavelength lidars at Cloudnet sites have been made so far by the PollyXT systems (Engelmann et al., 2016) at Leipzig, Finokalia, Limassol, and Punta Arenas. First tests with a different lidar system (MPIM) have also been performed for the Cloudnet site at Barbados. Here, the lidar-only target categorization could be successfully implemented. Fig. 10 shows a 24-hour measurement in June 2014 for which an intense dust layer (black) prevailed over the island. The dust had obviously the potential to influence the cloud formation of the Passat cumuli (bluish colours) as it occurred in the same height regions where cloud formation started. Furthermore, a down-mixing of the dust into the marine PBL (orange) was observed (brown, mixed dust).

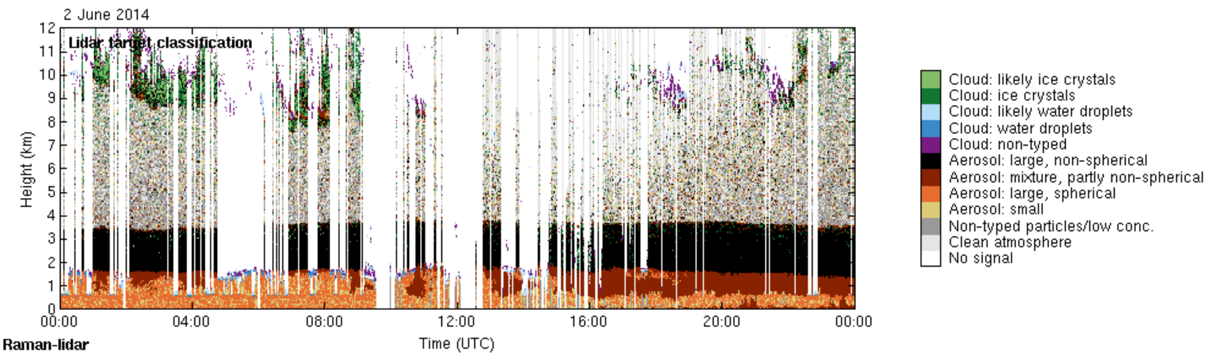

Figure 10. Lidar target categorization applied for the MPIM lidar at Barbados on 2 June 2014.

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In the near future, it is foreseen to have more continuously co-located high-power lidars and Cloudnet stations. The current lidars, which are not yet automated, could for example be upgraded or replaced by new systems.

During the project, also the first approaches for the combination of the lidar-only target categorization (see Fig. 10) with the Cloudnet target categorization were performed. An example for a measurement day in Cyprus is shown in Fig. 11.

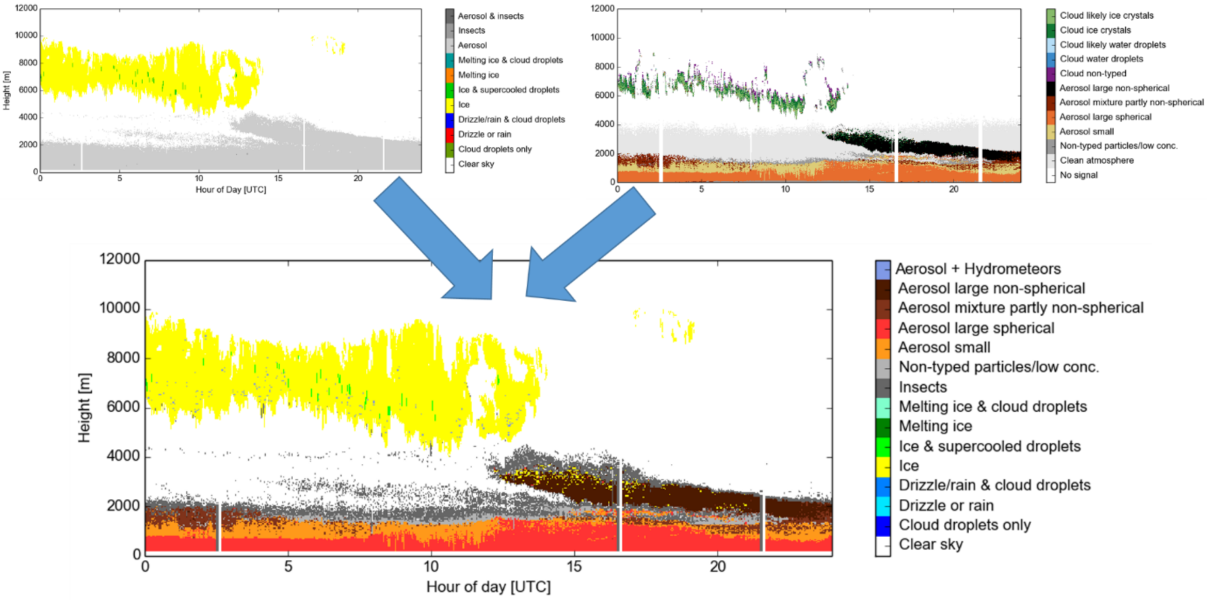

Figure 11. Cloudnet target mask (top left) and lidar-based target classification (top right) and the corresponding combined mask (bottom) at Limassol, Cyprus on 27 March 2017.

The standard Cloudnet classification is presented in the upper left panel. It shows cirrus clouds and undefined aerosol layers below. In contrast, the standard lidar-based target categorization (upper right) can distinguish the different aerosol types by size and shape, but captures the high-altitude clouds only at the bottom due to the instrument sensitivity. The combination of both masks (bottom panel) allows the characterization of the different aerosol types as well as the cloud properties and thus is well suited for aerosol-cloud-interaction studies. The development of the combined masks is ongoing, including uncertainty characterization (probably based on fuzzy logic). The operational implementation into the EARLINET and Cloudnet structures is planned.

In summary, harmonised, consistent retrievals have been developed in WP2 to allow for the implementation of multiwavelength lidars into the Cloudnet processing chain. As a first prerequisite, a new SCC module for high-resolution pre-processed lidar signals have been developed. Depolarization calibration and the absolute calibration of the lidar signals have been implemented in the EARLINET processing scheme so that now quantitative products from high-power lidars are available with high temporal resolution. Thanks to the activities for instrumental developments, long-term observations with continuously running lidars show a very good performance satisfying the requirements for newly developed lidar products with high temporal resolution, which are necessary for aerosol-cloud-interaction research. For that purpose, a lidar target categorization using particle-like properties have been developed. Finally, combined products using EARLINET lidars and Cloudnet instruments are now possible.

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- Implementation of water-vapour Raman lidars at selected Cloudnet and EARLINET sites

Water-vapour measurements based on the detection of Raman-scattered radiation are already performed at several EARLINET sites. According to the EARLINET Handbook of Instruments this capability is available for systems at the following stations: Athens (Associated Partner NTUA), Barcelona (UPC), Cabauw (KNMI), Bucharest (INOE), Granada (UGR), Barbados (Associated Partner MPIM), Leipzig (TROPOS, several systems), Kuopio (FMI), Palaiseau (CNRS), Lille (CNRS), Minsk (IPNASB), Napoli (CNR), Potenza (CNR), Finokalia (NOA) and Warsaw (IGF PAS). At the Cloudnet site of Lindenberg (DWD), a powerful water-vapour lidar is also available, but not as part of EARLINET.

For all lidar systems, a calibration with respect to water vapour is needed, which was previously done with sporadic radiosonde launches. Within the framework of ACTRIS, new methodologies for the calibration of water vapour signals from Raman lidar have been developed.

The automatic use of a microwave radiometer (MWR) for the calibration of a continuously measuring Raman system was finally achieved as an outcome of the Cloudnet training school at Cyprus in March 2017. Fig. 11, top panel, shows an example time series of water-vapour mixing ratio profiles, which are usually only available during night time.

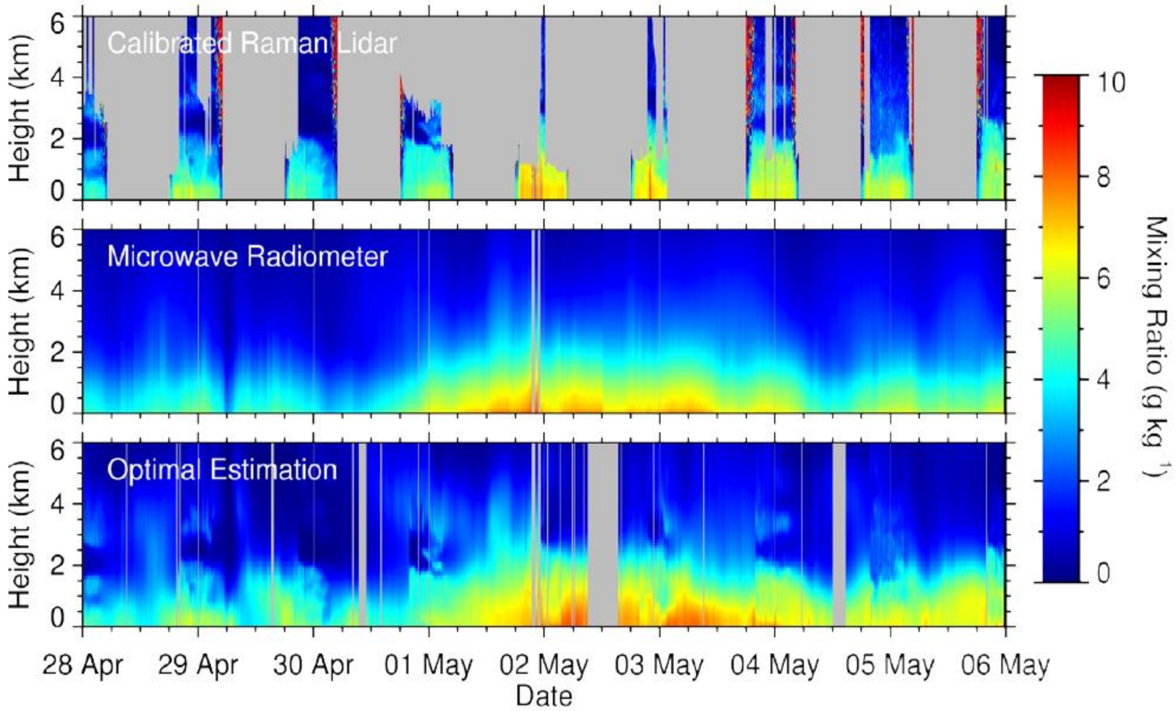

Figure 12. Temporal development of water-vapour mixing ratio profiles by (top) lidar PollyXT only, (middle) MWR only, and (bottom) combined retrieval based on optimal estimation.

The calibration was obtained from the MWR, which measures the total columnar water vapour in the atmosphere. Additionally, an optimal estimation technique was developed (Foth and Pospichal, 2017) to make best use of the synergies between Raman lidar and MWR to obtain 24-hour profiles of the water-vapour mixing ratio with respective uncertainty determinations. The outcome of this procedure for the example presented here is shown in Fig. 12, bottom panel.

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Beside the use of MWR, a new calibration technique for water-vapour Raman lidars in combination with photometer and model data was developed based on the ACTRIS data from Limassol, Cyprus (LACROS, TROPOS, Dai et el., 2018). Sun photometers are widely deployed at ACTRIS sites in contrast to radio soundings, which are sparse and often not co-located. Thus, this new technique is a promising approach for continuous calibration of lidars with water-vapour capabilities when MWR is absent. Fig. 13 shows the results from a long-term study in Cyprus with LACROS.

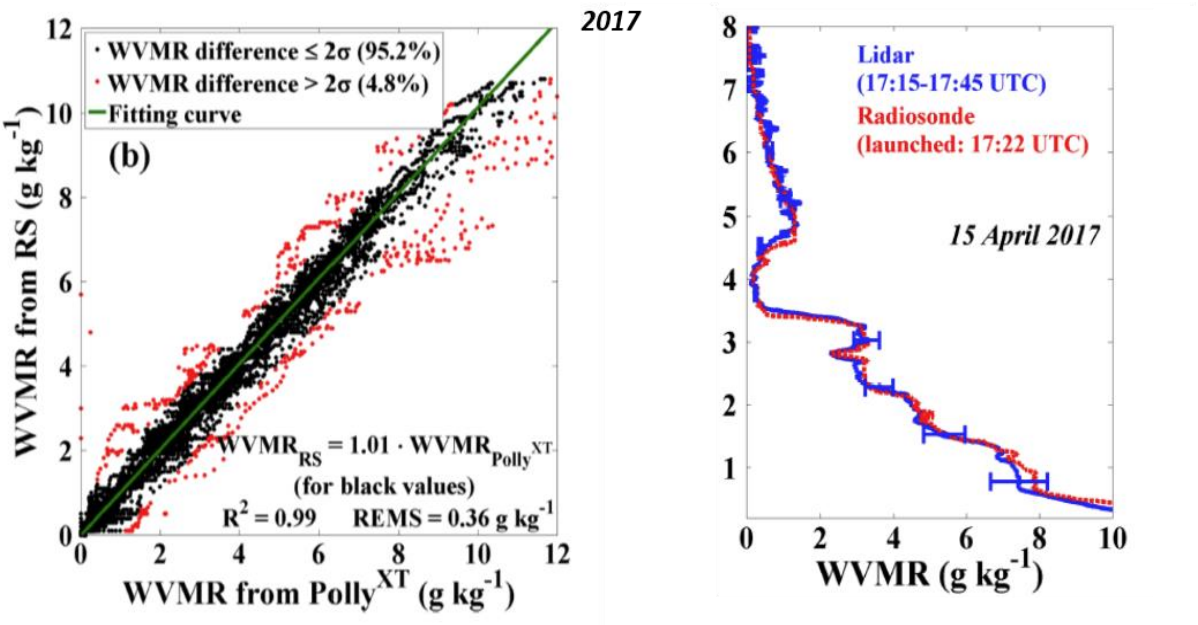

Figure 13. Overview of the new calibration method for water-vapour lidars with sun photometer and model data (WVMR – water-vapour mixing ratio).

Comparing the water-vapour measurements from the PollyXT lidar calibrated with sun photometer with the regular radio sounding (left panel), an excellent agreement with a slope of 1.01 and a R^2 of 0.99 was found. An example comparison of the calibrated lidar profile with a radiosonde on 15 April 2017 is plotted in the right panel, and again shows the high potential of this methodology. Thus, the method approved to be very accurate and applicable for other ACTRIS sites. The method has, e.g., been applied to the long-term ACTRIS measurements in Dushanbe, Tajikistan to characterize humidity conditions during dust events.

For continuously measuring lidars, this calibration constant seems to be very accurate and stable, as also shown in Fig. 9 for the example of Punta Arenas. Thus, one can assume that observations are reliable and good atmospheric data can be obtained, even when sun photometer data is not available, e.g., due to cloud presence.

Thanks to recent developments within ACTRIS, also lunar photometers are now available. It was shown during the project, that also this kind of photometer provides the possibility to calibrate water-vapour Raman lidar data as shown in Fig. 14. As the Raman lidar measurements are often restricted to night time, this additional feature is very valuable for high-quality observations.

In this context, it has to be emphasized that the presence of a photometer has been established as a requirement for the ACTRIS National Facilities dedicated to aerosol remote sensing, so that all ACTRIS

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aerosol lidar sites will have the instrumental setup for the calibration of the additional water-vapour signals.

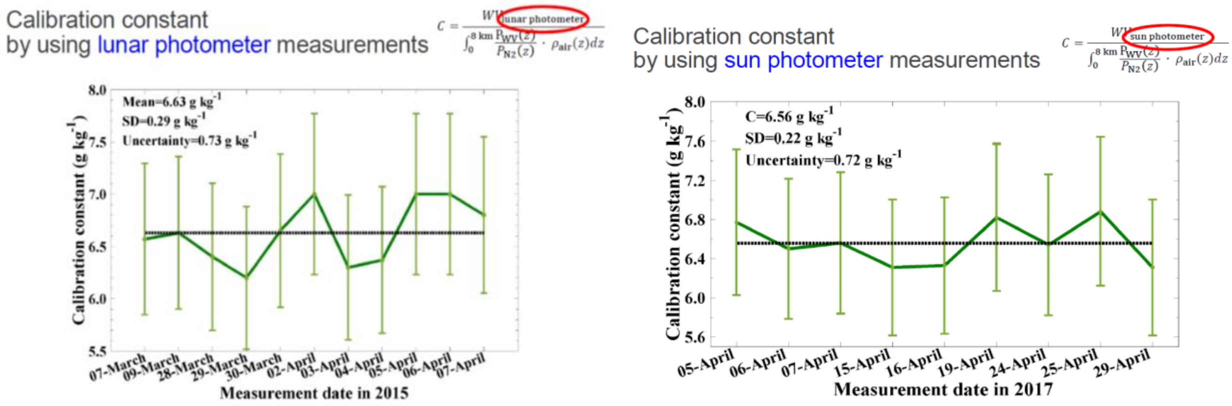

Figure 14. Water-vapour calibration constant for Raman lidar as retrieved by sun photometer (left) and lunar photometer (right) at Cyprus.

In summary, several methods have been developed for the calibration of ACTRIS Raman lidars with water-vapour measurement capabilities. These techniques have been successfully deployed at several instruments and locations, so that water-vapour profiles are now available at a number of ACTRIS sites. The knowledge of water vapour in the atmosphere is, as the turbulence characteristics, a prerequisite for aerosol-cloud-interaction studies and will be valuable auxiliary ACTRIS data.

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ACTRIS (www.actris.eu) is supported by the European Commission under the Horizon 2020 – Research and Innovation Framework Programme, H2020-INFRAIA-2014-2015, Grant Agreement number: 654109