Comparison of CALIPSO aerosol data with ground based lidar measurements

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ABSTRACT

In April 2006 the backscatter lidar CALIOP onboard of the CALIPSO satellite was launched as part of NASA's A-Train. The aim is to retrieve vertically resolved optical properties of clouds and aerosols, in particular profiles of extinction coefficient and particle depolarisation ratio. The derivation of extinction coefficients suffers from uncertainties in the estimation of the lidar ratio. As a consequence, validation is required. As part of a validation effort in the framework of EARLINET, the Meteorological Institute of the Ludwig-Maximilians-Universität performs measurements with the Raman lidar MULIS at Maisach (48.20°N, 11.25°E). The Raman lidar methodology allows determining extinction and backscatter coefficients without a priori knowledge of the lidar ratio.

Profiles of attenuated backscatter and of aerosol extinction coefficients derived from MULIS and CALIOP data are compared for a limited number of case studies. In case of stable weather conditions the agreement with respect to the identification of aerosol layers is good. Only very thin aerosol layers could not be retrieved as the CALIOP signals were below predetermined thresholds. The agreement of the extinction profiles is limited – the reasons are not necessarily deficiencies of the measurements or their evaluation, but they could also be due to the distance of the sub-satellite track from Maisach. However, unrealistically high aerosol extinction coefficients retrieved from CALIOP (in the order of 2 km^{-1}) let assume that the CALIOP aerosol/cloud discrimination sometimes fails or that ground returns may be misinterpreted in case of strong orography. Finally, we found cases which suggest amendments of CALIPSO's lidar ratio database.

1. OVERVIEW

Aerosols are an important component of the atmosphere. They influence the radiative household of the earth by direct effect as interaction between aerosol and radiation, and by indirect effect as cloud condensation nuclei. The difficulty in calculating these effects is the insufficient knowledge of the global distribution of aerosols both temporally and spatially.

To improve this knowledge, on 28th April 2006 the NASA launched the satellite Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) as part of the A-Train. On board is amongst other instruments the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). CALIOP is a two-wavelength backscatter lidar which also measures linear depolarisation at one wavelength. Its aim is to get daily profiles of extinction coefficients and linear particle depolarisation of clouds and aerosols around the whole globe.

To retrieve these profiles from the signals of a backscatter lidar, the ratio between the extinction and backscatter coefficients – the so called lidar ratio – has to be estimated. The lidar ratio for clouds has values of 15 to 20 sr, but for different types of aerosols these values can vary from 15 to 100 sr [1]. The assumption of a wrong lidar ratio can lead to strong errors of the extinction profiles. As a consequence, validation of the profiles of CALIOP is required. Especially measurements performed by ground based lidar systems achieve comparable profiles. As part of a validation effort in the framework of EARLINET, the Meteorological Institute of the Ludwig-Maximilians-Universität performs measurements at Maisach (48.20°N, 11.25°E). The Multiple wavelength lidar system MULIS [2] at this station is a Raman lidar, which enables to retrieve extinction and backscatter coefficients independently at 532 nm and at 355 nm and hence to determine the actual lidar ratios at these wavelengths. Furthermore the linear particle depolarisation ratio can be retrieved at 532 nm as with CALIOP. MULIS also measures the backscatter signal at 1064 nm, and with this it is well suited to validate the CALIOP data.

In the following it will be explained how the extinction profiles of CALIOP are produced. In chapters 3 and 4 the validation measurements will be presented and a comparison will be shown. Finally there will be a discussion about the occurrence of problems of the validation scheme and the algorithms of CALIOP.

2. THE LIDAR SYSTEM CALIOP ON-BOARD CALIPSO

CALIPSO as part of the A-Train orbits the earth 14.5 times per day and overflies every 16 days the same geo coordinates [3]. CALIOP is emitting laser pulses at 532 nm (linear polarised) and 1064 nm. It detects the total backscatter signals for both wavelengths, and additionally at 532 nm the perpendicular depolarised one.

2.1 CALIOP level 1B data

The received backscatter signals are averaged on-board vertically over height and partly horizontally over consecutive laser shots. Further calibrations are performed at the ground base to receive the attenuated backscatter signals, which are the range corrected lidar signals normalised with the lidar constant. They are available at the NASA Langley Research Center Atmospheric Science Data Center as

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level 1B data. These data are the basis for the following algorithms to calculate extinction profiles.

2.2 Retrieval of CALIOP level 2 data

To automatically retrieve the extinction coefficient out of lidar signals is a complex matter. For CALIOP there are three different sequences of algorithms for analysing the attenuated backscatter: the Selective Iterated Boundary Locator (SIBYL) [4], the Scene Classification Algorithms (SCA) [5] and the Hybrid Extinction Retrieval Algorithms (HERA) [6]. The input signal for their analysis is the Attenuated Scattering Ratio, i.e. the ratio between the total attenuated backscatter signal (received by measurement) and the “clear air” attenuated backscatter signal (calculated with ECMWF data).

For the preanalysis the signals are horizontally averaged over 5 km ground track (equivalent to 15 laser shots) to receive one profile. This profile is then scanned by the SIBYL to search deviations from the background signal. These deviations are so-called features like clouds, aerosols or ground return. The algorithm starts at the top of the signal (30km a.s.l.) and scans the profile down to the ground. To detect a feature and to specify base and top of this feature several altitude and noise dependent thresholds concerning signal strength and thickness of layer have to be exceeded. Because every feature is weakening the backscatter signal below it, the profile is recalibrated with the optical thickness of the overlying feature before further analysis of the profile.

After their localization, the SCA classifies each feature. In the first step the class of the feature (“clear air”, cloud, aerosol, stratospheric feature - cloud or aerosol, surface, subsurface, no signal, invalid) is determined using parameters like strength of the integrated attenuated backscatter, volume depolarisation ratio and height of the feature. In the second step the classified feature is specified into different types. In the class of aerosols, there are six different types: desert dust, biomass burning / smoke, clean continental, polluted continental, marine aerosol and polluted dust. For this typification additional parameters are used like colour ratio (ratio between integrated attenuated backscatter of 1064 nm to 532 nm), geographical position or temperature at feature top and base. For each type and wavelength there are values allocated in look-up-tables for the lidar ratios and the multiple scattering factors. If a layer is elevated and the air below and above is classified as clear air (no feature detected), lidar ratio and multiple scattering factor can also be iteratively calculated.

Under use of these values, HERA are calculating the extinction coefficient profiles for the feature classes cloud and aerosol. Therefor different algorithms are used, like the Newton-Raphson algorithm based on iteration. Especially during summertime the analysis of boundary layer aerosol is often complicated by small scale convective clouds at boundary layer top. These are filtered using a special averaging scheme.

The final products of these algorithms are separated in profile and layer data, in different resolutions, and in cloud and aerosol data. In the further comparison of this abstract, only profile and layer data for aerosol were used. At the moment the CALIOP aerosol profile data (Version 2.02) are released with a horizontal resolution of 40 km (equivalent to 120 laser shots) instead of 5 km to get better signal-to-noise ratio.

3. VALIDATION MEASUREMENTS WITH MULIS

The validation measurements with MULIS are performed at every overpass of CALIOP if the footprint passes within 100 km radius around the station Maisach near Munich, Germany, and if the weather conditions allow it, which means no precipitation, no low clouds and no fog. Within a 16 day cycle of CALIPSO, there are two overpasses during daytime with distances from the footprint of CALIOP to Maisach of about 50 km, and two overpasses during night with distances of about 85 km respectively 35 km.

Several parameters can be compared, like the presence of aerosol layers, their base and top, the attenuated backscatter signals or the extinction coefficients. For this purpose the attenuated backscatter signal, which is comparable to the CALIOP signal, is recalculated from the particle extinction and backscatter coefficients retrieved by MULIS and from the temperature and pressure profiles of a radiosonde near Maisach. At the moment neither the product uncertainties nor the linear particle depolarisation are given in the CALIOP level 2 data (version 2.01 + 2.02). They are expected in the next version of the data.

Although more than 20 comparison measurements have been performed in Maisach during night overpasses since the launch of CALIPSO, the presence of clouds during the overpass of CALIPSO narrows down the usable cases to only a few regarding the comparison of aerosol profiles.

4. COMPARISON OF MULIS AND CALIOP DATA

The comparison of the data of CALIOP and MULIS will be shown for three cases, two night overpasses (20th September 2007, 27th June 2008) and one daytime measurement (5th May 2008).

4.1 20th September 2007

The 20th September 2007 is an applicable day for a validation because of stable weather conditions. The overpass was during night at 01:40:07 UTC in a distance of 82.3 km of Maisach. In Figure 1 are shown the attenuated backscatter at 1064 nm and 532 nm, and the particle extinction coefficient and the lidar ratio at 532 nm. The average time for the MULIS data was from 01:31 to 02:00 UTC. As can be seen in the profiles of the attenuated backscatter and extinction coefficient, the same structures of the aerosol layers are observed by both instruments. The layer at 2 km is slightly stronger and the layer top is about 0.2 km higher in MULIS measurements. This difference can be explained by the horizontal distance of 82.3 km between the two profiles. The CALIOP algorithms defined for the whole layer between 0.5 and 2.1 km the aerosol type “smoke” and allocated therefore the lidar ratio value 70 sr for 532 nm. This value agrees well with the measured values of MULIS, the aerosol classification seems to be successful.

4.2 27th June 2008

On the 27th June 2008 the overpass was during night time at 01:35:07 UTC in a distance of 34.9 km. At this day, there were no clouds detected above Maisach but over South Germany during the overpass of CALIOP.

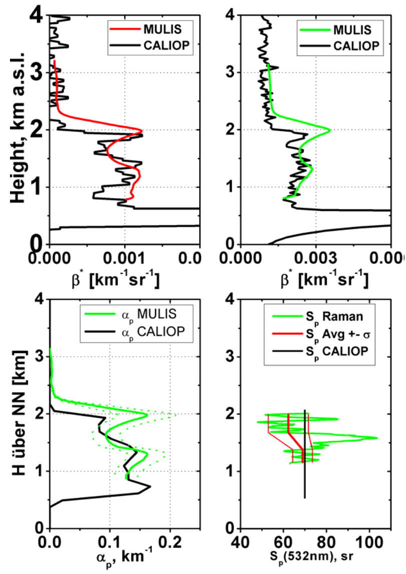

Figure 1. *Measurements of CALIOP and MULIS on 20th September 2007, with attenuated backscatter β* at 1064 nm, β* at 532 nm, particle extinction coefficient α_p at 532 nm (MULIS uncertainty estimates dotted), and lidar ratio S_p at 532 nm. CALIOP profiles are averaged over 01:40:07-01:40:13 UTC, MULIS profiles over 01:31–02:00 UTC.*

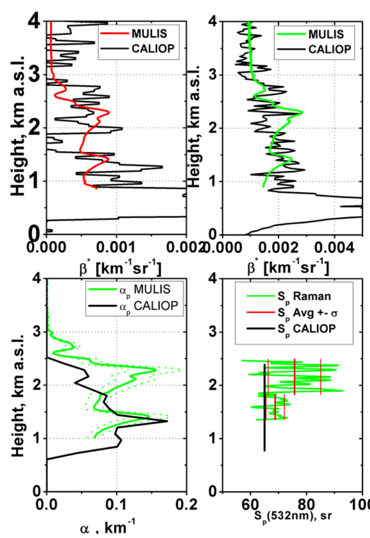

Figure 2. *Measurements of CALIOP and MULIS on 27th June 2008, as in figure 1. CALIOP profiles are averaged over 01:35:04-01:35:10 UTC, MULIS profiles over 01:26–01:50 UTC.*

Figure 2 shows the comparison of measurements of CALIOP and MULIS on 27th June 2008, with attenuated backscatter at 1064 nm and at 532 nm and particle extinction coefficient and particle lidar ratio at 532nm. MULIS profiles were calculated using a signal average between 01:26 and 01:50 UTC, for CALIOP data from 01:35:04 to 01:35:10 UTC were uses.

Because of clouds during CALIOP measurements, the attenuated backscatter signals are averages of only few laser shots and thus show a low signal-to-noise ratio. The structures of the particle extinction profiles are the same for MULIS and CALIOP, but the magnitude of the layer at 2.3 km is higher for MULIS. This is connected with the differing lidar ratios at this height; the classification of the aerosol type from the CALIOP algorithm results in polluted dust with a lidar ratio of 65 sr, while higher values of about 78 sr result from the measurements of MULIS.

4.3 05th May 2008

On the 5th May 2008 the overpass of CALIPSO was during daytime at 12:25:33 UTC in a distance of 59.6 km. Because of daytime measurement, the noise of the attenuated backscatter signals of CALIOP is too strong. Hence structures can't be seen clearly and are therefore not shown, and also the measurement and comparison of the lidar ratio is not possible.

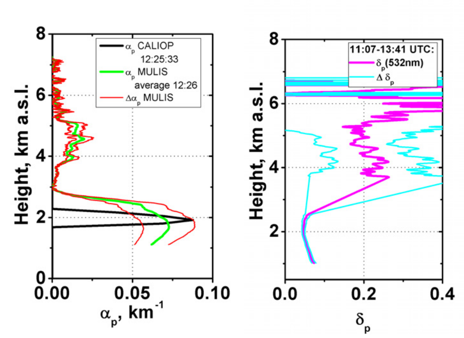

Figure 3. *Particle extinction coefficients α_p of CALIOP and MULIS at 05. May 2008 around the overpass at 12:25 UTC (left) and linear particle depolarisation ratio δ_p (right) derived from MULIS at the same time, with upper and lower uncertainty estimates for the MULIS values $\Delta\alpha_p$ and $\Delta\delta_p$.*

During the overpass, low small scale clouds were disturbing the measurements. The extinction coefficients of MULIS (Figure 3) show an elevated aerosol layer at 3.8 - 5.2 km, which wasn't detected by CALIOP. The evening measurement of MULIS on the same day indicates that this layer was very homogeneous and stable over time. The high linear particle depolarisation ratio in this layer of values of about 0.2 let us assume mineral dust as aerosol type.

Also the aerosol layer measured by MULIS at 1-3 km is not good reproduced by the CALIOP data. The layer is too thin (from 1.7 to 2.2 km). Probably there were problems with the filtering of the low clouds during the averaging scheme.

5. DISCUSSION

The comparison shows, that the classification of aerosols and the calculation of the extinction coefficients are successful under certain conditions like stable homogeneous aerosol layers. But even on this case study with three measurement examples several problems of validation and of CALIOP algorithms could be detected.

5.1 Validation uncertainties

There are several problems of a validation of a satellite lidar with a single ground based lidar system. As mentioned before, the nearest overpass of CALIOP is still further than 30 km away of Maisach. This distance can lead to strong differences in the vertical distribution of aerosols. Also effective measurement performances are depending on good weather conditions. Both problems can be decreased using a network of ground based lidar stations, as done in Europe by EARLINET.

5.2 Problems with received level 2 aerosol profile data

The comparison of the three different days shows several disagreements concerning the Level 2 aerosol profile data.

Because of the given thresholds and renormalisations below features, often thin elevated layers can be missed by the CALIOP algorithms as demonstrated with the comparison of 05th May 2008 (4.3). The same day hints to problems with the filtering of the low clouds out of the averaged signals to gain aerosol profiles.

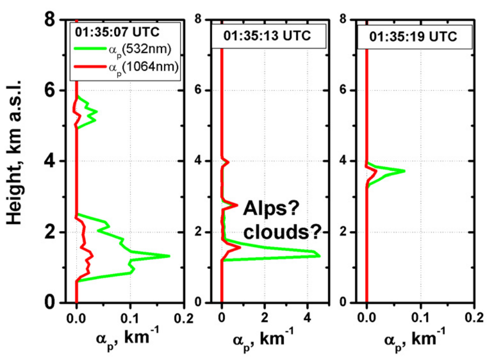

Figure 4.*Particle extinction coefficients α_p at 532 nm (green) and 1064 nm (red) of CALIOP aerosoldata for three consecutive 40-km averages on 27. June 2008: 01:35:07, 01:35:13, 01:35:19 UTC. The middle profile shows values of more than a factor of 20 greater than before and after at both wavelengths.*

Another problem at the extinction values of CALIOP is the occurrence of strong values in singular profiles. In Figure 4 are shown the extinction coefficients at wavelengths 532 nm (green) and 1064 nm (red) of level 2 CALIOP aerosol profile data for three following 40-km averages on 27. June 2008: 01:35:07, 01:35:13, 01:35:19 UTC. The middle profile shows in both wave-lengths values of more than a factor of 20 greater than the one before and after. These values are way too strong for extinction coefficients of aerosols and mete-orologically not explainable. The reasons for these peaks are yet not worked out. One possibility is the wrong classification of a cloud feature as an aerosol. Another reason could be a problem of separating the strong surface backscatter signal during strong orographic altitude changes. The middle profile is an average over 40 km horizontally while CALIPSO was crossing part of the Alps. The differences in surface altitude were more than 1 km within the averaging time of this profile. Consequently, using CALIOP level 2 data one should not use a single profile without comparison with the neighbouring profiles.

SUMMARY

CALIOP as a space born backscatter lidar is a big advancement for studying the global distribution of aerosols. Because of several assumptions validation measurements with ground based lidar systems are required to improve the products of CALIOP. Such validation measurements were performed at Maisach with the Raman lidar MULIS during overpasses of CALIPSO. Three different days – two nighttime, one daytime - were compared to CALIPSO level 1B and level 2 data in respect of aerosol profiles. It was found that on stable weather conditions the CALIOP data are consistent with the MULIS data.

It is shown that there are still several problems in the CALIOP validation scheme and in the CALIOP algorithms for the detection of aerosol layers and for the calculation of extinction coefficients. Especially the detection of thin layers can fail. In some cases singular profiles with uncommonly high values for extinction coefficients (> 1 km^{-1}) were observed. Reasons for this could be a wrong classification of feature type or a wrong interpretation of ground return. In the upcoming version of CALIOP level 2 data it is expected that some of the aforesaid problems are decreased by improvements of the algorithms. Then further validation will be necessary.

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