GROUND-BASED VALIDATION OF CALIPSO OBSERVATIONS OF DUST AND SMOKE IN THE CAPE VERDE REGION

M. Tesche[1], U. Wandinger[2], A. Ansmann[2], D. Althausen[2], D. Müller[2,3], and A. Omar[4]

[1]*Department of Applied Environmental Science (ITM), Stockholm University, Svante Arrhenius väg 8, 10691 Stockholm, Sweden, Presenting author e-mail: matthias.tesche@itm.su.se*
[2]*Leibniz Institute for Tropospheric Research (IfT), Permoserstraße 15, 04318 Leipzig, Germany*
[3]*now at: Science Systems and Applications Inc., NASA Langley Research Center, Hampton, Virginia, USA*
[4]*NASA Langley Research Center, Hampton, Virginia, USA*

ABSTRACT

Ground-based depolarization Raman lidar measurements during the second Saharan Mineral Dust Experiment (SAMUM-2) in January/February and May/June 2008 are used for validation of measurements of the lidar aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite within the dusty environment of the Cape Verde region. 15 out of 33 considered cases were found suitable for such a comparison. Night-time overpasses seem to provide most reliable data. The best agreement was found for the 532-nm backscatter coefficient while CALIPSO tends to slightly underestimate the 532-nm extinction coefficient. Depolarization ratios given in the CALIPSO level 2 version 3 files were found to be larger and much noisier than the ones calculated from profiles of the cross-polarized and total backscatter coefficients given in the same file. Furthermore, calculated values seem to agree better with ground-based measurements. CALIPSO backscatter coefficients at 1064 nm are generally higher than ground-based values in cases of pure dust. Consequently, the backscatter-related Ångström exponents for dust do not agree with findings of the SAMUM-2 summer campaign. 1064-nm backscatter coefficients from CALIPSO and BERTHA are in good agreement for the winter measurements when mixed dust/smoke plumes are present over the Cape Verde region.

1. INTRODUCTION

Since June 2006, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO, *Winker et al.* 2009) satellite provides the scientific community with a vertically resolved global view of atmospheric aerosols. First studies of the CALIPSO data set were rather qualitative and dealt with the investigation of the vertical extent of aerosol layers and regimes or single events of aerosol transport. Numerous efforts were taken to validate CALIOP measurements, e.g., *McGill et al.* [2007]; *Burton et al.* [2010]. However, the studies available in the literature are mostly validating the identification of vertical features or the accuracy of level 1 products. Fewer case studies actually validate the final level 2 products of the CALIPSO retrieval. Most of the validation studies were performed at established lidar sites which are usually located in polluted urban areas and at mid-latitudes. Validations of the performance of the CALIPSO data retrieval in environments dominated by mineral dust or mixtures of dust and other aerosol types are scarce. Measurements with the Backscatter Extinction lidar–Ratio Temperature Humidity Apparatus (BERTHA, *Althausen et al.* 2000) lidar of the Leibniz Institute for Tropospheric Research (IfT), Leipzig, Germany, during the second Saharan Mineral Dust Experiment (SAMUM-2, *Tesche et al.* 2009, 2011) at Cape Verde provide a unique opportunity to validate CALIPSO level 2 products in an environment of long-range transport of pure and mixed mineral dust plumes.

2. INSTRUMENTS

2.1. BERTHA

BERTHA measures elastically backscattered light at the emitted laser wavelengths of 355, 400, 532, 710, 800, and 1064 nm, and Raman signals of water vapor at 660 nm and of nitrogen at 387 and 607 nm [*Althausen et al.*, 2000]. The depolarization ratio is measured at 710 nm and can be converted to 532 nm using a parameterization based on collocated observations with a system operating at this wavelength [*Tesche et al.*, 2011]. Profiles of particle extinction coefficients at 355 and 532 nm are calculated from the Raman signals. Temporal averaging and vertical smoothing is used to reduce the statistical error to values of 10%–25%. Systematic uncertainties caused by the removal of Rayleigh-scattering and air-density effects from the backscatter signals are of the order of 5%–10%.

2.2. CALIOP

The elastic-backscatter lidar CALIOP emits light at 532 and 1064 nm. The system features three detection channels. To allow for depolarization-ratio profiling, the backscattered signal at 532 nm is split into light that is polarized parallel and perpendicular to the plane of polarization of the emitted linearly polarized laser light. A total signal is detected at 1064 nm. An overview of the instrument and the data retrieval algorithms can be found in, e.g., *Winker et al.* [2009] and *Omar et al.* [2009].

3. COMPARED PARAMETERS

All parameters chosen for this comparison effort refer to particles. Subscripts are added to mark the respective wavelength. The compared parameters are the backscatter coefficients β_{532} and β_{1064}, the extinction coefficient

Table 1: CALIPSO overpasses within a distance of 500 km from Cape Verde that could be compared to the ground-based measurements. Times and dates are given in UTC and for 2008, respectively. The last two columns give the height range and the along-track latitudinal interval identified to be most reliable for comparison for the individual days, respectively.

CALIPSO overflights			**BERTHA measurements**			**comparison for**	
date	**time**	**distance to Praia**	**date**	**time**	**delay**	**heights**	**latitudes**
25 Jan	1515	161 km to the west	25 Jan	1215–1658	0 h	1.3–3.0 km	12.0-15.0°N
3 Feb	1509	4 km to the east	3 Feb	1120–1610	0 h	0.5–4.8 km	10.0-16.0°N
5 Feb	1422	325 km to the east	5 Feb	2000–2236	7 h	3.0–4.5 km	14.0-16.0°N
6 Feb	0245	441 km to the east	6 Feb	2146–2252	5 h	3.3–5.0 km	14.0-16.0°N
8 Feb	1457	487 km to the west	7 Feb	2127–2256	16 h	2.4–4.5 km	12.0-15.0°N
11 Feb	0328	46 km to the west	10 Feb	2332–0442	0 h	2.6–4.6 km	13.0-15.0°N
12 Feb	1503	164 km to the east	12 Feb	2010–2252	6 h	1.2–3.7 km	14.0-17.0°N
13 Feb	0253	280 km to the east	12 Feb	2010–2252	5 h	1.4–3.8 km	13.0-16.0°N
28 May	0258	441 km to the east	28 May	1014–1121	8 h	2.0–4.0 km	14.0-16.0°N
31 May	0327	362 km to the west	30 May	2011–2305	5 h	1.5–4.5 km	14.5-15.5°N
3 June	1458	171 km to the east	3 June	2330–0220	12 h	1.1–5.3 km	13.5-16.0°N
11 June	0309	127 km to the east	10 June	2134–0001	4 h	0.8–5.0 km	14.0-16.0°N
15 June	1528	478 km to the west	14 June	2133–2317	18 h	1.5–4.5 km	16.0-18.0°N
16 June	0341	351 km to the west	15 June	2042–2332	5 h	1.8–5.9 km	12.0-15.0°N
17 June	1516	153 km to the west	17 June	0215–0505	12 h	1.1–5.8 km	14.0-16.0°N

α_{532}, the extinction-to-backscatter (lidar) ratio S_{532}, the backscatter-related Ångström exponent $\mathring{a}^{\text{bsc}}_{532/1064}$, and the depolarization ratio δ_{532}. The latter was taken from the CALIPSO level 2 version 3 files ($\delta^{\text{file}}_{532}$) and calculated from the profiles of the cross-polarized and total backscatter coefficients as

$$\delta^{\perp/\parallel}_{532} = \frac{^{\perp}\beta_{532}}{\beta_{532} - {}^{\perp}\beta_{532}} \,. \quad (1)$$

4. METHODOLOGY

BERTHA measurements during SAMUM-2 were performed during noon, after sunset, and during CALIPSO overpasses in the vicinity of the ground site at Cape Verde [*Tesche et al.*, 2011]. For the comparison presented here, only cases in which CALIPSO passed BERTHA at a distance $<$500 km are considered [*Kovacs*, 2006]. CALIPSO overpasses to the west/east of Cape Verde were connected to the ground station through HYSPLIT forward/backward trajectories starting/arriving over BERTHA at various heights. The suitable temporal delay between a CALIPSO overpass and a BERTHA measurement is given by the time difference between the start/arrival of a trajectory at Cape Verde and its intersection with the CALIPSO ground track. Concurrently, the intercept points mark the along-track latitudinal intervals for averaging CALIPSO profiles that most likely probed the same air parcels as BERTHA at Cape Verde. The usage of this approach enabled matching CALIPSO overpasses to BERTHA measurements over distances of several hundred kilometers and time periods of up to 18 h. During SAMUM-2, 33 CALIPSO overpasses occurred at a distance of less than 500 km from the BERTHA site. 15 of these overpasses were found suitable for comparing aerosol profiles of BERTHA and CALIPSO. A detailed overview of these cases is given in Table 1. Within the respective along-track latitudinal range, CALIPSO profiles were averaged and smoothed with a window length of 660 m. The same was done for BERTHA measurements [*Tesche et al.*, 2011]. Conditions that inhibited a comparison during the remaining 18 CALIPSO overpasses were the occurrence of low and high clouds which attenuate the signal of the ground-based and spaceborne system, respectively, as well as low aerosol load which results in a low signal-to-noise ratio.

5. EXAMPLE CASE

The application of the comparison methodology is presented here for the example of the CALIPSO overpass at around 1528 UTC on 15 June 2008 and the corresponding BERTHA measurement between 2133 and 2317 UTC on 14 June 2008 during SAMUM-2b (see Table 1). CALIPSO observations in terms of curtain plots of the level 1 532-nm attenuated backscatter coefficient between 0 and 30°N and the vertical feature mask, aerosol subtype mask, β_{532}, and $\delta^{\text{file}}_{532}$ between 10.0 and 23.2°N according to level 2 version 3 of the CALIPSO retrieval are shown in Figure 1. The CALIPSO retrieval properly distinguishes between clean air, aerosols, and clouds (Figure 1b) and identifies a deep elevated dust plume and mixed aerosol in the boundary layer (Figure 1c). CALIPSO observations between the white lines in Figure 1 were averaged for the comparison with BERTHA measurements during the previous night. The aerosol profiles obtained with the two instruments are shown in Figure 2. For the example day, best agreement is found for β_{532}, though a 532-nm dust lidar ratio of 40 sr is assumed in the CALIPSO retrieval [*Omar et al.*, 2009] whereas SAMUM observations generally showed higher values of 55 sr (see Figure 2d and *Tesche et al.* [2009]). Multiple-scattering effects could explain this

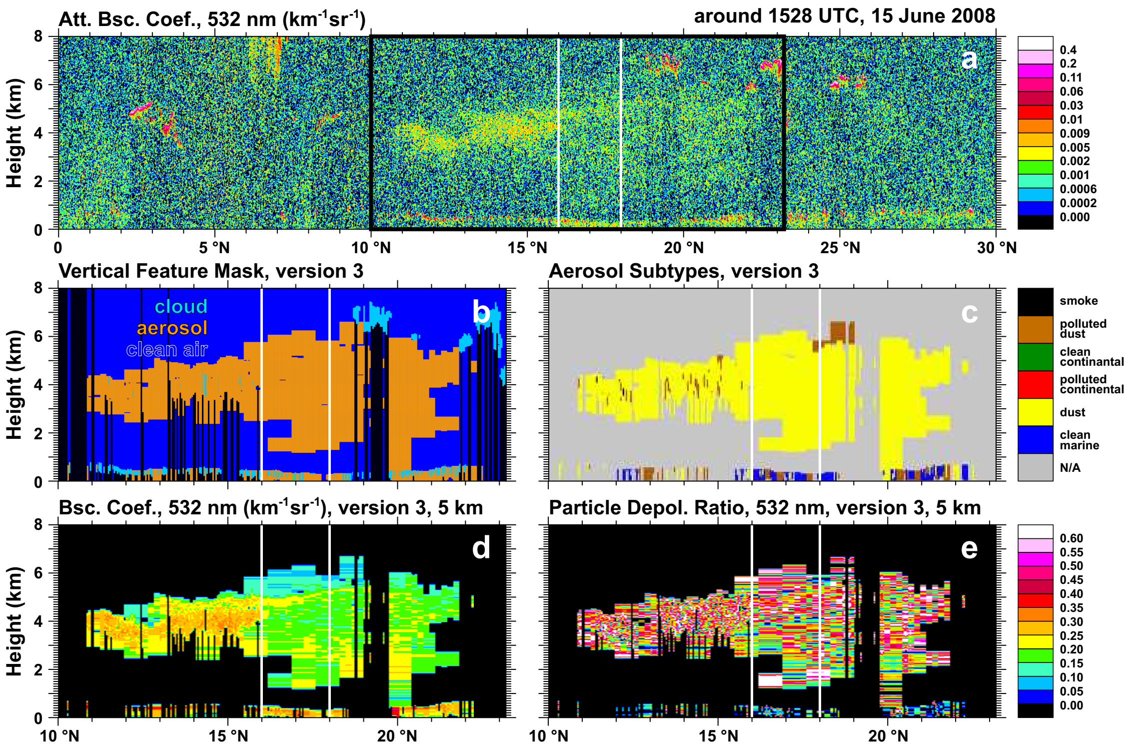

Figure 1: CALIPSO measurement during an overpass 478 km to the west of Praia at around 1528 UTC on 15 June 2008 in terms of latitude-height plots of the 532-nm attenuated backscatter coefficient between 0 and 30°N (a) and the vertical feature mask (b), the aerosol subtype mask (c), the 532-nm backscatter coefficient (d), and the 532-nm particle depolarization ratio (e) between 10 and 23.2°N (black frame in a). White lines mark the interval chosen for the comparison to BERTHA measurements (see Table 1).

effect [*Wandinger et al.*, 2010]. α_{532} from CALIPSO is lower than from BERTHA observations since β_{532} is multiplied with the low lidar ratio of 40 sr. β_{1064} from CALIPSO observations is overestimated, which in turn leads to an underestimation of $\mathring{a}^{\text{bsc}}_{532/1064}$.

Dust depolarization ratios measured with BERTHA for the example case agree with the value of 0.31 found during SAMUM-1. The CALIPSO observations show somewhat lower values for both $\delta^{\text{file}}_{532}$ and $\delta^{\perp/\parallel}_{532}$. Note that the overpass occurred during the day and a lower signal-to-noise ratio might have decreased the detection sensitivity. For the presented overpass the depolarization ratio taken from the CALIPSO file agrees quite well with the one calculated according to Eq. (1). For most of the other cases given in Table 1, $\delta^{\perp/\parallel}_{532}$ is much closer to BERTHA obser-

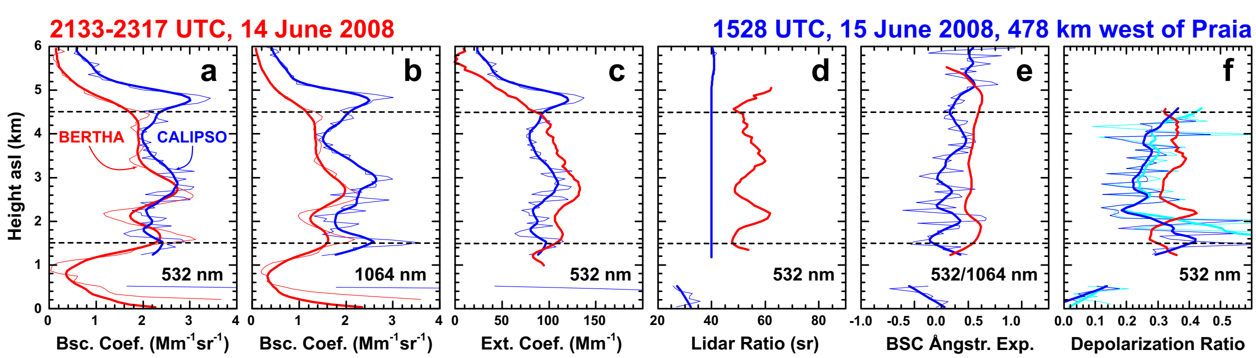

Figure 2: Height profiles of β_{532} (a), β_{1064} (b), α_{532} (c), S_{532} (d), $\mathring{a}^{\text{bsc}}_{532/1064}$ (e), and δ_{532} (f) as measured with BERTHA (red, 2133–2317 UTC, 14 June 2008) and CALIPSO (blue, 1528 UTC, 15 June 2008, 478 km west of Cape Verde). Thin and bold lines refer to unsmoothed and smoothed (660-m window length) profiles, respectively. Light and dark blue lines in (f) refer to $\delta^{\text{file}}_{532}$ and $\delta^{\perp/\parallel}_{532}$, respectively. Dotted lines mark the vertical range chosen to be most suitable for comparison (see Table 1).

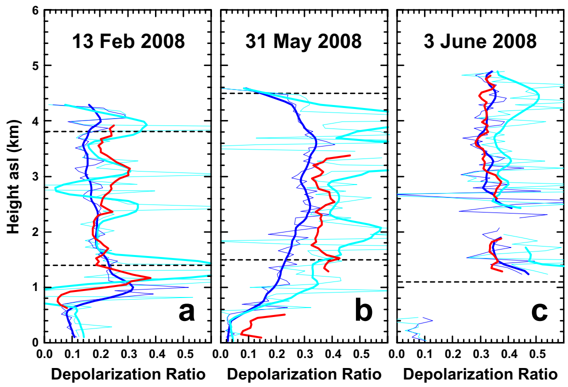

Figure 3: Same as Figure 2f but for the comparison of CALIPSO overflights on 13 February, 31 May, and 3 June 2008.

vations and also less noisy than $\delta_{532}^{\text{file}}$. This is illustrated in Figure 3, which shows depolarization-ratio profiles for the comparison of CALIPSO overflights on 13 February, 31 May, and 3 June 2008. The cause of the deviation between $\delta_{532}^{\text{file}}$ and $\delta_{532}^{\perp/\parallel}$ is currently under investigation and might be related to different averaging approaches in the CALIPSO retrieval and the analysis according to Eq. (1).

6. DISCUSSION AND CONCLUSIONS

The comparison of CALIPSO observations to ground-based measurements during SAMUM-2 showed that the findings are strongly dependent on the comparison methodology. Measurements at a ground site need to be connected to a CALIPSO overpass in a proper way. This can best be achieved by the use of trajectories. Furthermore, the width and location of the averaging window for calculating mean CALIPSO profiles for comparison needs to be adapted for every single case. The latter is of special importance in cases of inhomogeneous aerosol conditions along the satellite track.

The initial aerosol classification scheme seems appropriate to obtain aerosol profiles that are in reasonable agreement with coincident ground-based measurements. The results of the final aerosol subtype product could be improved through the utilization of the particle depolarization ratio instead of the approximate particle depolarization ratio which is currently used in the aerosol classification of the level 2 version 3 retrieval. In cases of low backscatter ratio, low volume depolarization ratios could still result in high particle depolarization ratios. Only the use of the latter can provide a reliable discrimination between pure mineral dust and mixtures of dust and other aerosol types (referred to as polluted dust in the CALIPSO data retrieval). Furthermore, particle depolarization ratios could be used together with the geographical location of the measurement to estimate the other aerosol types that contribute to the dust mixture. As for the improvements suggested by *Wandinger et al.* [2010], this would require an implementation of recurring procedures to the CALIPSO data retrieval.

Several conclusions can be drawn after considering the comparison of CALIPSO observations and BERTHA measurements within the dusty environment of Cape Verde during SAMUM-2: (1) best agreement is generally found for the backscatter coefficient at 532 nm (through the use of an effective dust lidar ratio of 40 sr, see *Wandinger et al.* 2010); (2) depolarization ratios calculated according to Eq. (1) are in better agreement with the BERTHA depolarization ratios than the ones given in the CALIPSO files; (3) depolarization ratios within the lowermost layers only seem to be reliable during nighttime overpasses; (4) CALIPSO backscatter coefficients at 1064 nm are much higher than ground-based values in cases of pure dust (SAMUM-2b); and consequently (5) the backscatter-related Ångström exponents for dust do not agree with findings of SAMUM-1 and SAMUM-2b.

ACKNOWLEDGMENTS

CALIPSO data used in this study were obtained from the NASA Langley Research Center Atmospheric Science Data Center (http://eosweb.larc.nasa.gov).

REFERENCES

Althausen, D., D. Müller, A. Ansmann, U. Wandinger, H. Hube, E. Clauder, and S. Zörner (2000), Scanning six-wavelength eleven-channel aerosol lidar, *J. Atmos. Ocean. Techn.*, *17*, 1496–1482.

Burton et al. (2010), Using airborne high spectral resolution lidar data to evaluate combined active plus passive retrievals of aerosol extinction profiles, *J. Geophys. Res.*, **115**, 10.1029/2009JD012130.

Kovacs, T. (2006), Comparing MODIS and AERONET aerosol optical depth at varying separation distances to assess ground-based validation strategies for spaceborne lidar, *J. Geophys. Res.*, **111**, 10.1029/2006JD007349.

McGill et al. (2007), Airborne validation of spatial properties measured by the CALIPSO lidar, *J. Geophys. Res.*, *111*, doi:10.1029/2005JD006569.

Omar, A. H., et al. (2009), The CALIPSO automated aerosol classification and lidar ratio selection algorithm, *J. Atmos. Oceanic Technol.*, *26*, doi:10.1175/2009JTECHA1231.1.

Tesche, M., et al. (2009), Vertical profiling of Saharan dust with Raman lidars and airborne HSRL in southern Morocco during SAMUM, *Tellus*, **61B**, 10.1111/j.1600-0889.2008.00390.x.

Tesche, M., et al. (2011), Profiling of Saharan dust and biomass burning smoke with multiwavelength polarization Raman lidar at Cape Verde, *Tellus*, **63B**,10.1111/j.1600-0889.2011.00548.x.

Wandinger, U., et al. (2010), Size matters: Influence of multiple scattering on CALIPSO light–extinction profiling in desert dust, *Geophys. Res. Lett.*, **37**, 10.1029/2010GL042815.

Winker, D. M., et al. (2009), Overview of the CALIPSO mission and CALIOP data processing algorithms, *J. Atmos. Oceanic Technol.*, *26*, 2310-2323.