

Towards an aerosol classification scheme for future EarthCARE lidar observations and implications for research needs

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Abstract

Owing to the high variability of aerosols, and their different impact on the Earth's climate system, aerosol type classification from satellite measurements is of high importance. Polarization sensitive lidar measurements on board the future Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) satellite mission will provide information to distinguish different aerosol types. We analyze whether former classification schemes based on lidar measurements at 532 nm are applicable to EarthCARE measurements at 355 nm. We compare coordinated lidar measurements at both wavelengths performed during five field experiments; adapt thresholds for aerosol classification with future spaceborne lidar measurements and identify limitations of the current state of knowledge.

Keywords: aerosols; EarthCARE; lidar; remote sensing; classification

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1. Introduction

Aerosols are a fundamental part of the Earth's atmosphere with various impacts on the Earth's radiation budget and hydrological cycle. These numerous effects are not yet fully understood (Forster *et al.*, 2007; Penner *et al.*, 2011; Bond *et al.*, 2013). A main reason is the large variability and the limited knowledge of the temporal and spatial distribution of the optical and microphysical properties of aerosols on global scales (Penner *et al.*, 2001). In addition the sign and the magnitude of the radiative forcing strongly depend on the vertical layering of aerosols and the presence of clouds underneath the aerosol layers (Forster *et al.*, 2007). To improve our understanding regular observations with high vertical and horizontal resolution are required. Spaceborne measurements with elastic backscatter lidar systems such as the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) system (Winker *et al.*, 2007) on board the Cloud-Aerosol Lidar and Pathfinder Satellite Observations (CALIPSO) mission gather such altitude-resolved information. However, for the classification of different aerosol types assumptions are necessary (Omar *et al.*, 2009) which may cause misclassification (Kacenenbogen *et al.*, 2011; Burton *et al.*, 2013). Advanced lidar systems like polarization sensitive Raman lidar systems (Ansmann *et al.*, 1992) or high spectral resolution lidar (HSRL) systems (Piironen and Eloranta, 1994; Esselborn *et al.*, 2008) are capable of distinguishing different aerosol types as shown, e.g. by Groß *et al.* (2011a, 2013b), Weinzierl *et al.* (2011), and Burton *et al.* (2012), as they are capable of directly retrieving

the lidar ratio without assumptions of a priori information. At the moment, these lidar systems are either airborne or ground-based, but the next generation satellite mission of the European Space Agency (ESA) together with the Japan Aerospace Exploration Agency (JAXA), the Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission will be equipped with a polarization sensitive HSRL system (ATLID – Atmospheric Lidar) operating at 355 nm. Current aerosol classification schemes (Burton *et al.*, 2012; Groß *et al.*, 2013b) were developed based on airborne HSRL measurements at 532 nm. It is an open question how the present classification schemes can be transferred to measurements with the ATLID system on EarthCARE at 355 nm. In this work, we present an analysis of the wavelength dependence of the lidar ratio S_p and the particle linear depolarization ratio δ_p , required for an aerosol classification with ATLID measurements, for five main aerosol types and aerosol mixtures of the Earth's atmosphere – mineral dust, mineral dust mixtures, marine aerosols, biomass burning mixtures and volcanic ash.

2. Methods

2.1. Data basis

In this study, we use data from five different field experiments: the Lindenberg Aerosol Characterization Experiment (LACE) (Ansmann *et al.*, 1998), the Saharan mineral dust experiments, SAMUM-1 (Heintzenberg, 2009) and SAMUM-2 (Ansmann *et al.*, 2011), the European integrated project on

Table 1. Mean values and mean systematic uncertainties for the intensive optical properties S_p and δ_p of different aerosol types measured with WALES, MULIS and POLIS. Numbers in brackets give the number of measurements.

Aerosol type	WALES 532 nm	MULIS 532 nm	POLIS 355 nm	Field experiment	Reference
S_p (sr)					
Saharan dust	48 ± 5 (4)	56 ± 5 ^a (13)		SAMUM-1	Esselborn <i>et al.</i> (2009); Tesche <i>et al.</i> (2009)
			58 ± 8 (6)	SAMUM-2	Groß <i>et al.</i> (2011a)
Dust mixture	50 ± 4 (5)		54 ± 3 (6)	SAMUM-2	Groß <i>et al.</i> (2011a, 2013b)
ABB mixture	63 ± 7 (5)	69 ± 8 (13)	76 ± 12 (12)	SAMUM-2	Groß <i>et al.</i> (2011a, 2013b)
CBB	69 ± 17 (1)			LACE98	Groß <i>et al.</i> (2013b)
Marine ^b	18 ± 5 (5)	18 ± 2 (2)	18 ± 4 (4)	SAMUM-2	Groß <i>et al.</i> (2011a, 2013b)
Anthropogenic	56 ± 6 (4)			EUCAARI	Groß <i>et al.</i> (2013a)
Volcanic ash		50 ± 5 (2)	55 ± 5 (2)	Eyjafjalla	Groß <i>et al.</i> (2012)
δ_p (%)					
Saharan dust	32 ± 2 (4)	32 ± 2 (18)		SAMUM-1	Esselborn <i>et al.</i> (2009); Freudenthaler <i>et al.</i> (2009)
			25 ± 2 (6)	SAMUM-2	Groß <i>et al.</i> (2011a)
Dust mixture	27 ± 2 (5)	24 ± 4 (5)	17 ± 3 (6)	SAMUM-2	Groß <i>et al.</i> (2011a, 2013b)
ABB mixture	14 ± 2 (5)	16 ± 1 (13)	16 ± 3 (12)	SAMUM-2	Groß <i>et al.</i> (2011a, 2013b)
CBB	7 ± 2 (1)			LACE98	Groß <i>et al.</i> (2013b)
Marine ^b	3 ± 2 (5)	2 ± 1 (2)	2 ± 1 (4)	SAMUM-2	Groß <i>et al.</i> (2011a, 2013b)
Anthropogenic	6 ± 1 (4)			EUCAARI	Groß <i>et al.</i> (2013a)
Volcanic ash		37 ± 2 (2)	35 ± 2 (2)	Eyjafjalla	Groß <i>et al.</i> (2012)

ABB, African biomass burning; CBB, Canadian biomass burning.

^aCoordinated ground-based measurements with the BERTHA system (Althausen *et al.*, 2000) of TROPOS, Leipzig, as no Raman lidar measurements were performed with MULIS during SAMUM-1. Both systems were located next to each other in a horizontally very homogeneous atmosphere.

^bRelative humidity in the marine aerosol layer $\geq 50\%$.

Aerosol Cloud Climate and Air Quality Interactions (EUCAARI) (Kulmala *et al.*, 2009), and the Eyjafjalla volcanic ash measurements at Munich university (Groß *et al.*, 2012; Wiegner *et al.*, 2012). During these field experiments, aerosol properties have been studied by an extensive set of aerosol *in situ* instruments on board the DLR Falcon research aircraft by an airborne HSRL system measuring the lidar ratio and the particle depolarization ratio at 532 nm and by two ground-based polarization sensitive Raman lidar systems of the Ludwig-Maximilians-Universität (LMU), München, operational at 532 and 355 nm. For the volcanic ash measurements, no airborne HSRL measurements were performed. On the basis of this comprehensive dataset, we assess whether the aerosol classification scheme developed for 532 nm (Groß *et al.*, 2013b) is applicable to future EarthCARE lidar measurements at 355 nm. Although several studies on lidar derived aerosol optical properties have been performed, we restrict our comparisons to the above mentioned dataset to avoid uncertainties which might result from different instrument setups or combinations, or different calibration techniques. Furthermore, only few studies with simultaneously performed lidar measurements of the lidar ratio and the particle linear depolarization ratio at 355 and 532 nm together with *in situ* observations are reported in the literature so far. Discussions of the used dataset to former studies can be found in the references listed in Table 1. Information about the corresponding *in situ* measurements can be found in Groß *et al.* (2013b) and Weinzierl *et al.* (2011) and the references therein.

2.2. Lidar systems

In this section, we give a short overview of the lidar systems used to examine the wavelength dependence of S_p and δ_p for different aerosol types. Details on instrument performance and measurement uncertainties are discussed in the corresponding references.

POLIS (Groß *et al.*, 2008) is a ground-based small portable lidar system developed and operated by the Meteorological Institute of the LMU. Measurements were either performed in the depolarization mode, measuring the cross- and co-polarized lidar return at 355 nm, or in the Raman mode measuring the elastically scattered signal return at 355 nm and the N_2 -Raman shifted return at 387 nm.

MULIS (Freudenthaler *et al.*, 2009) is a ground-based mobile multi-wavelength lidar system developed and operated by the Meteorological Institute of the LMU. It provides measurements of the elastically backscattered signals at 355, 532 (co- and cross-polarized) and 1064 nm, and of the N_2 -Raman shifted signals at 387 and 607 nm.

WALES (Water vapor Lidar Experiment in Space) (Wirth *et al.*, 2009), developed and operated by the DLR, is primarily an airborne differential absorption lidar (DIAL) system for water vapor measurements within the absorption band at 935 nm whose primary objective was the preparation of a space borne mission mapping the global water vapor distribution. Additional polarization sensitive aerosol channels at 532 and 1064 nm and a high spectral resolution capacity at 532 nm (Esselborn *et al.*, 2008) enable simultaneous aerosol measurements.

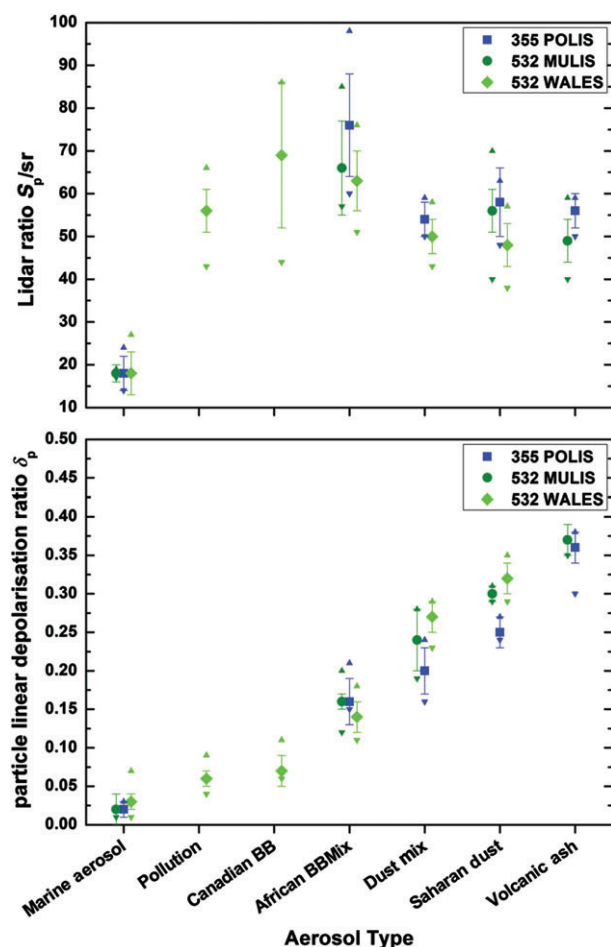


Figure 1. Lidar ratio (top panel) and particle linear depolarization ratio (bottom panel) of the mean values found for the different aerosol types at 355 and 532 nm from POLIS (355 nm), MULIS and WALES (both 532 nm) measurements. The error bars show the mean systematic uncertainties; the triangles show the maximum and minimum values.

3. Results and discussion

3.1. Wavelength dependence of optical properties

Figure 1 shows the mean values of the lidar ratio S_p and the particle linear depolarization ratio δ_p for different aerosol types. The error bars indicate the mean systematic errors of these values. A general information about the error calculation of the different variables is given by Freudenthaler *et al.* (2009), Esselborn *et al.* (2008) and Groß *et al.* (2011b). The errors of the single measurements used for this work are discussed in corresponding references listed in Table 1. No wavelength dependency of the lidar ratio is visible for marine aerosol, Saharan mineral dust and dust mixtures (Figure 1, top panel). For volcanic ash and African biomass burning mixtures, the mean S_p value at 355 nm is slightly higher than at 532 nm, but considering the measurement uncertainties this difference is not significant. In the bottom panel of Figure 1, the particle linear depolarization ratio δ_p is depicted for different aerosol types. No wavelength dependency for marine aerosol, African biomass burning mixtures and volcanic ash is

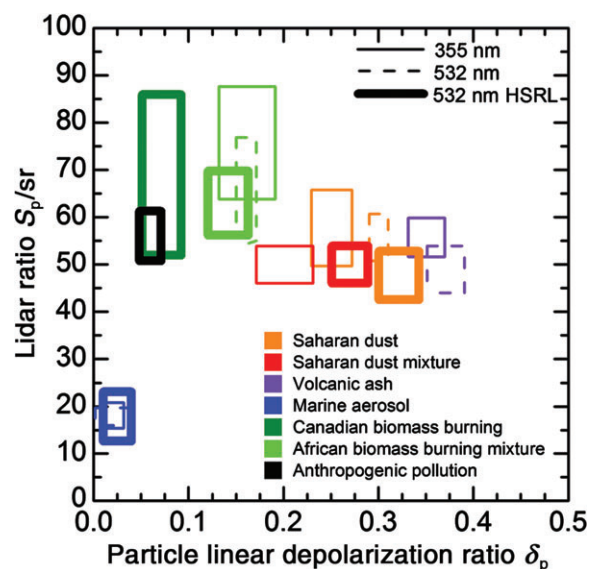


Figure 2. Aerosol lidar ratio versus particle linear depolarization ratio for various atmospheric aerosol types measured with the lidar systems POLIS at 355 nm, and MULIS and WALES at 532 nm. The rectangles denote the mean values plus/minus the mean uncertainties as summarized in Table 1.

observed. In contrast, we find significantly lower values of δ_p for Saharan dust at 355 nm, and consequently also for dust mixtures at which it has to be kept in mind that δ_p in dust mixtures depends on the type and the amount of aerosol mixed with Saharan dust. In our case, we see a strong contribution of Saharan dust most probably mixed with marine aerosols, which is in good agreement to former findings (Mona *et al.*, 2006). As we do not have coordinated S_p and δ_p measurements at 355 and 532 nm for pure biomass burning aerosol and anthropogenic pollution airmasses from the three used lidar systems, the wavelength dependency for these two aerosol types will not be discussed here.

Table 1 summarizes the main findings of this section for the different aerosol types. Besides the values for S_p and δ_p also the measurement uncertainties and the corresponding references are summarized.

3.2. Classification scheme

In this section, we discuss the applicability of the previously (Burton *et al.*, 2012; Groß *et al.*, 2013b) developed aerosol classification scheme at 532 nm for EarthCARE measurements at 355 nm. Similar to Burton *et al.* (2012) and Groß *et al.* (2013b), the intensive lidar optical parameters (S_p and δ_p) are presented in a two-dimensional S_p – δ_p parameter space in Figure 2, which additionally shows the values for both wavelengths, 355 and 532 nm, in one plot.

The cluster for marine aerosol agrees well for the different wavelengths, confirming the applicability of the classification thresholds derived by Groß *et al.* (2013b) at 532 nm also for 355 nm. For volcanic ash and African biomass burning mixture the data clusters at both wavelengths overlap. However, the mean values and uncertainty ranges at both wavelengths differ.

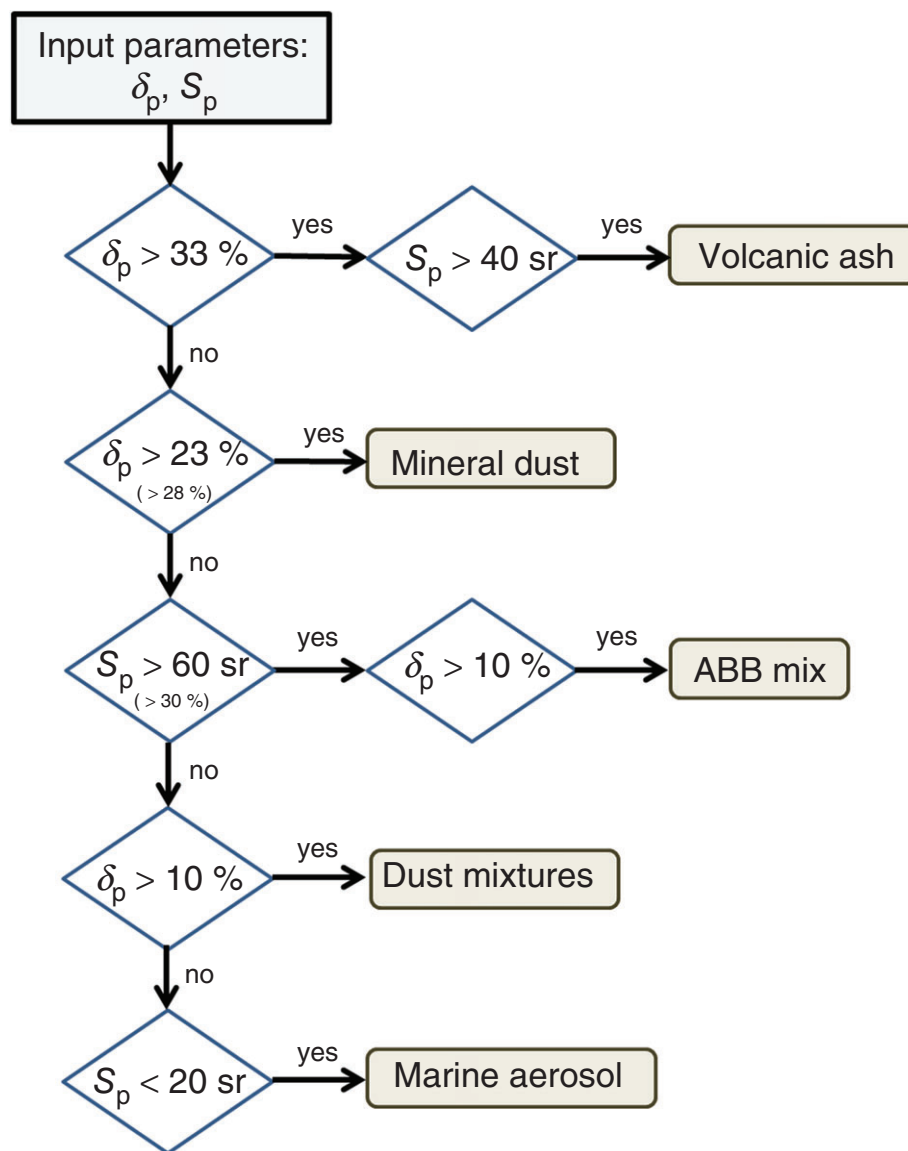


Figure 3. Schematic flowchart of the aerosol type classification based on lidar ratio S_p and particle linear depolarization ratio δ_p information at 355 nm; values at 532 nm [adapted from Groß *et al.* (2013b)] are shown in brackets. ABB mix denotes African biomass burning mixtures.

For African biomass burning mixture the thresholds adapted by Groß *et al.* (2013b) retain ($S_p > 60$ sr and $\delta_p > 10\%$). For volcanic ash the thresholds for the aerosol classification scheme at 355 nm must be adapted to values higher 40 sr for S_p and 33% for δ_p . The same holds for Saharan dust, were we do not see an overlap of the data clusters at all. The thresholds for the classification at 355 nm are 23% and 33% as lower and upper δ_p values, respectively, and 60 sr as upper threshold for S_p .

Figure 3 presents the adapted aerosol type classification thresholds for lidar measurements (e.g. by ATLID on EarthCARE) at 355 nm on the basis of the results of this study. Using this classification scheme, it has to be kept in mind that some aerosol types show only small differences in the lidar optical properties (see Figures 1 and 2) and therefore they are harder to distinguish than other aerosol types. In addition, highly accurate lidar

measurements with small uncertainties are necessary for correct aerosol type classification.

3.3. Discussion

The optical properties of aerosols are correlated with the aerosols microphysical properties like particle size, particle shape and chemical composition (Gasteiger *et al.*, 2011). During short- to long-range transport, the microphysical properties can be modified by various mechanisms (Weinzierl *et al.*, 2011), and with that the optical properties and the measurement values of S_p and δ_p and their wavelength dependency can be influenced. For example, Amiridis *et al.* (2009) found from regular Raman lidar measurements that the values and wavelength dependence of the lidar ratio for biomass burning aerosols may change with time since emission. This may be caused by changing of the microphysical properties during transport. Another

indication for the modification of optical properties during transport was found for mineral dust: during a strong Saharan dust outbreak in 2008 dual-wavelength depolarization measurements were performed over Central Europe (Wiegner *et al.*, 2011). High δ_p values of 30% were found at 355 nm compared to values of 25% during SAMUM-2. However, the measurements by Wiegner *et al.* (2011) cover only one case, and in addition, the dust load was very low resulting in large measurement uncertainties preventing a clear conclusion. More measurements of S_p and δ_p in mineral dust plumes at different age after emission are necessary to draw final conclusions on changes of S_p and δ_p as a result of aging processes.

Measurements of fresh and aged aerosol plumes, in particular of biomass burning aerosols and mineral dust, at different wavelengths are therefore crucial. Furthermore the aerosol classification scheme at 355 nm has to be extended for further basic aerosol types like anthropogenic pollution and cirrus clouds.

4. Conclusion

We presented a comparison of a comprehensive dataset of coordinated measurements with polarization sensitive Raman and HSRL lidar systems at 355 and 532 nm and examined the wavelength dependency of the lidar optical aerosol parameters, S_p and δ_p . On the basis of our analysis, we adapted the thresholds of the already existing aerosol classification scheme at 532 nm so that this classification scheme is applicable for future satellite lidar observations at 355 nm on board EarthCARE. Our study shows that for some aerosol types (e.g. marine aerosol) the classification thresholds found for 532 nm are also applicable at 355 nm. For other aerosol types (e.g. mineral dust), the classification values have to be adapted for 355 nm.

We see this study only as a starting point for an aerosol classification scheme at 355 nm. Currently the dataset to develop a comprehensive classification scheme for global satellite lidar measurements at 355 nm is limited, especially with respect to different measurement locations and to aerosol mixtures. Thus questions concerning the influence of aerosol aging, natural variability, and complex aerosol mixtures on a global classification scheme cannot be answered yet. Future research activities are crucial to extend the database for aerosol type classification at 355 nm. Especially, more measurements of basic aerosol types such as anthropogenic pollution or fresh biomass burning aerosol are necessary. In addition, special attention should be paid to the investigation of the effect of aerosol aging processes on the lidar optical parameters S_p and δ_p at 355 nm. Such investigations may result in different classification thresholds for fresh and aged aerosols of the same type. The Saharan Aerosol Long-Range TRansport and Aerosol Cloud interaction experiment (SALTRACE: <http://www.pa.op.dlr.de/saltrace/>) performed in June/July 2013 in the Caribbean may

help to answer some of the aging-related questions. Furthermore, model calculations using complex particle shapes and *in situ* measurements as input parameters are helpful to study the sensitivity of the lidar optical properties S_p and δ_p on the different microphysical properties.

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