# AFRICAN DUST OVER OCEAN AND CONTINENT BY COUPLING ACTIVE AND PASSIVE SPACEBORNE SENSORS

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## ABSTRACT

Spaceborne backscatter lidar systems allow new insights on the vertical distribution of aerosols, and more specifically for aerosols over land, where retrievals from passive sensors are known to be more difficult due to surface contribution. Here we revisit mineral dust aerosol characterization above Northern Africa, Tropical Atlantic Ocean (TAO) and Mediterranean Sea, by coupling LITE and Meteosat-5 spaceborne observations. Sensitivity tests indicate that the aerosol scattering coefficient is retrieved within a 20% relative uncertainty.

Airmass trajectories allow us to retrieve the vertical profile of aerosol optical properties over the continent using the BER (backscatter-to-extinction ratio) determined over the ocean. Results confirm a large dispersion of the BER values which is not attributed to errors in the method. We further analyse the performance required from space observations to reduce the errors on the estimate of aerosol radiative impact.

## 1. INTRODUCTION

Due to their spectral characteristics and their high optical depth, mineral dust has been shown to have a significant direct radiative impact [1]. The difficulty encountered to study their radiative impact is due to the heterogeneity of their concentrations and properties. Furthermore satellite measurements are difficult to use over desert, due to the poorly known and high reflectance of the surface.

Numerous passive instruments on spaceborne platforms have been used to measure the column dust aerosol optical thickness over low albedo surface. But only TOMS (Thematic Ozone Mapper Spectrometer) [2] and Meteosat infrared channels [3] have yet provided valuable aerosol information over desert regions. Moreover, these passive instruments alone give only access to integrated information in the atmospheric column, and too sparse quantitative information above continents.

The visible/near-infrared backscatter lidar is one of the most powerful and sensitive tool for the detection of atmospheric scattering layers with a high vertical resolution. Indeed, the Lidar In-Space Technology Experiment (LITE) [4], and the Geosciences Laser Altimeter System (GLAS) mission [5] has clearly demonstrated the great potential of a spaceborne lidar for the determination of improved cloud and aerosol climatologies at global scale.

The synergy between active and passive measurements can lead to significant improvement of the lidar inversion. We present in this work the potential of the coupling between a spaceborne lidar (LITE) and a geostationary satellite (Meteosat-5) to retrieve the aerosol optical properties over both ocean and continent, with a focus on African dust. Therefore, a processing chain has been implemented. Results and validation of the method is presented. The error on the dust radiative impact has been assessed for this synergy, and for the coupling of other active and passive instrument.

## 2. METHODOLOGICAL SYNERGY BETWEEN LITE AND METEOSAT-5

We consider spaceborne observations taken 10 to 20 september 1994. They include data from the passive radiometer on board the European geostationary satellite Meteosat-5, and from the active lidar instrument during the LITE mission.

Visible Meteosat-5 Images at full resolution (2.5 x 2.5 $km^2$ at nadir) taken daily at 11:00, 12:00 and 13:00 UTC are used to retrieve the AOT over the ocean [6]. The LITE data correspond to raw lidar signals at 532 nm obtained from several nighttimes orbits that crossed north western Africa, the tropical Atlantic Ocean (TAO) and showing significant desert dust aerosol plumes.

Using the retrieved Meteosat AOTs as a constraint in the inversion procedure of lidar signal, it is possible to determine the BER (Backscatter-to-Extinction Ratio), inverse of the so-called lidar ratio, characterizing the aerosols properties [7]. It can thus vary with altitude, but to avoid a too large complexity we considered two simplified models of aerosol vertical distribution over the ocean. The first one (Method I) is assuming a constant BER in the atmospheric column, by making the hypothesis of an efficient mixing of the dust aerosol in the low troposphere. The Method II is considering different values of BER in the MArine Boundary Layer (MABL) and the dust aerosol layer.

In fact, for space observations, multiple-scattering effect is also affecting the scattering of the propagating laser light [8]. In the lidar equation this effect can be considered as changing the BER to an apparent BER defined by BER/$\eta$, where $\eta$ is the multiple scattering factor. Hence the BER considered in the inversion is the apparent BER (ABER) including multiple scattering effects.

The lidar-derived integrated aerosol optical thickness is then compared with the Meteosat-5 AOT over the same oceanic region, and convergence is achieved when the difference stays in the range of uncertainty linked to the Meteosat-5 retrieved AOT.

## 3. RESULTS OVER OCEANIC SURFACES

The main dust plume, where the stronger value of AOT has been registered, is located between 12°N and 27°N, and, -40°W and 14°W, corresponding to the African west coast area. Due to the clouds screening effect, the number of inverted LITE profiles is limited to ~4100 on aerosol events. The mean ABER retrieved by the method I in this area, is close to 0.024±6.10$^{-3}$ sr$^{-1}$ for a mean AOT of 0.38±0.15. The first inversion of LITE profiles using method I shows the existence of two aerosol layers, wich could be composed with different aerosol types. The use of method II is then more appropriate to analyze such cases. The AOT in the MBL is found to be 0.071±0.044. The mean value of the ABER for the dust aerosols is now to ~0.023 sr$^{-1}$ with a standard deviation ~7 10$^{-3}$ sr$^{-1}$, corresponding to lidar ratios of ~40 ±13 sr.

## 4. DUST AEROSOLS PROPERTIES OVER CONTINENT SURFACES

Inversion of lidar data over the continental surfaces needs the a priori knowledge of the ABER, variable characterizing the aerosol type. We try therefore to make the correspondence between aerosols observed above continental surfaces, and the ones observed above oceanic surfaces where the BER value has been previously retrieved.

In order to investigate the transport and the source regions of the dust plumes seen by LITE, we have used Meteosat IR images (IDDI index [3]**)**, and airmass trajectories thanks to the HYSPLIT transport model (HYbrid Single-Particle Lagrangian Integrated Trajectory model).

Simulation of dust emission occurrences is also made by comparison of erosion threshold, 10-m wind velocity $V_t$ [9], and surface wind velocities from the analyzed wind fields of the European Centre for Medium-range Weather Forecast (ECMWF).

A very good agreement is observed between the source areas determined from LITE data and from the two other methods. Discussion about the location of dust sources is made in Berthier et al. [10]. The main activity sources identified by these methods for the duration of the LITE mission are the Erg Chech and the El Djouf area (Algeria), the west of the Hoggar mountain (the Tanezrouft), Sahelian sources (Mali) and also the Moroccan west coast.

Hence, the ABER that can be retrieved over the TAO to make the inversions of LITE measurement over the desert. The ABER means value of the method II (0.023 sr$^{-1}$ for dust is then used to inverse the LITE data over land. About 3000 cloud-free lidar profiles can be inversed over the continent. Indeed, spaceborne lidar offers the possibility to retrieve the AOT over continent in presence of high surface albedo (arid and semi-arid surfaces). The mean value of the dust AOT assessed over the continent is 0.39 at 532 nm with a standard deviation of 0.10, very close to the one retrieved over the TAO.

## 5. DISCUSSION ON THE LIDAR-RETRIEVED PARAMETERS

Errors on the AOT over land are due to error in the BER values used for the lidar data inversion and on transport analysis. Errors on AOTs and on aerosol extinction coefficients can thus be related to several independent main causes : **(1)** the uncertainty on the boundary condition defined in the well-known solution of the Bernouilli's differential form, and the uncertainty on the a priori knowledge of the vertical profile of the Rayleigh backscatter coefficient as determined from ancillary measurements or atmospheric model interpolation, **(2)** the statistical fluctuations of the measured signal associated with random detection processes, **(3)** the uncertainty on the Meteosat-5 derived AOT, **(4)** the uncertainty due to the horizontal resolution of Meteosat-5, **(5)** the uncertainty due to the multiple scattering effect, and **(6)** the uncertainty due to the temporal synchronization between LITE and Meteosat-5.

First of all, the effect of the cause **(1)** is retrieved negligible compared to the others (less than 2%).

The effect of the horizontal resolution of Meteosat-5 **(4)** has been studied by successive degradation of the resolution, but seem to have a weak influence on the retrieval of the ABER, due to homogeneous properties of the dust plume (variation of ~3.10$^{-4}$ sr$^{-1}$ between the lower and the better resolutions ).

The effect of the time delay between Meteosat-5 and LITE **(6)** is evaluated by using as constraints in the inversion of the lidar profiles the Meteosat AOT from the days before, coincident and after the LITE measurements. The differences in the distribution of ABER are weak, proving that the aerosol plumes are very stable in time.

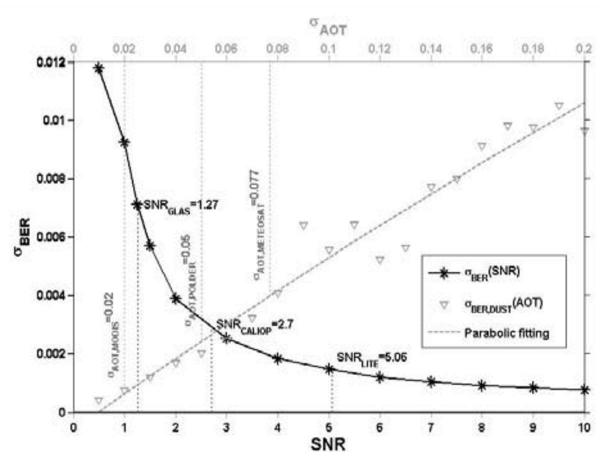

Fig. 1. Standard deviation on the retrieved ABER against the lidar signal to noise ratio (SNR) and the standard deviation on the AOT [10].

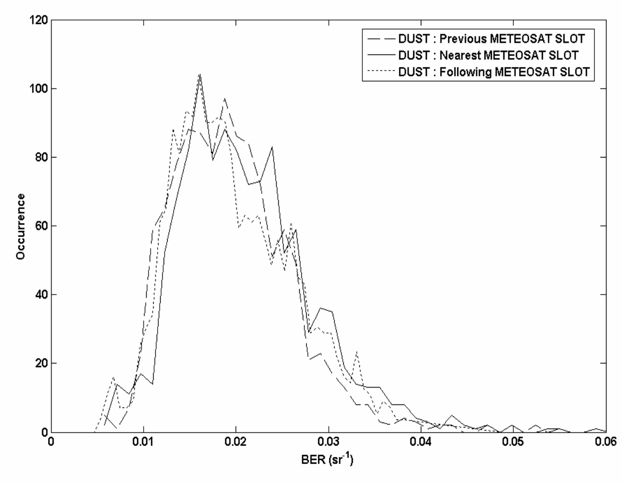


Fig. 2. Probability Density Function of the Aerosols BER retrieved by the method II over the TAO for dust aerosols. The calculations have been performed for the previous, following and nearest Meteosat-5 observations. [10]

A Monte Carlo approach has been implemented in order to assessing the effect of lidar signal noise **(2)** for the inversion of a synthetic atmosphere. From this statistics studie, the values of the standard deviation on ABER are found between $10^{-3}$ and 1.9 $10^{-3}$ $sr^{-1}$. The cases for different SNR, and particularly the SNR of the spaceborne lidar of the GLAS mission and one of the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) onboard the CALIPSO satellite have been also analyzed and reported in Fig. 1.

In order to estimate the influence of the error on Meteosat-retrieved AOT **(3)**, a Monte Carlo approach has been also used. The random realizations have been done considering a normally distributed AOT around 0.31 and the standard deviation on Meteosat-retrieved AOT of 0.05. Due to this error sources, the standard deviations on the ABER is ~4.3 $10^{-3}$ $sr^{-1}$. It is greater than the ones due to the SNR by a factor of ~2. The use of the new generations of passive sensors as Meteosat Second Generation (MSG), the Moderate Resolution Imaging Spectroradiometer (MODIS) and the POLarization and the Directionality of the Earth's Reflectances (POLDER) onboard the Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) will be a great advance to improve the synergy between spaceborne lidar and passive instrument. Fig. 1 gives also the standard deviation on the ABER against the uncertainty on the AOT for dust aerosols. The retrieved error obtained with the inversion MODIS data, the Advanced Very High Resolution Radiometer (AVHRR) data and POLDER data is highlighted in Fig. 1. The improvement of the AOT retrieval for the new generation of passive spaceborne instruments will conduct to a very significant decrease in the BER error.

The multiple scattering effect **(5)** on spaceborne lidar must be considered. If the values of $\eta$ are supposed to vary between 0.6 (AOT~0.40) and 0.9 (AOT~0.2), as given in Karyampudi et al. [4], they lead to standard deviations of 3 $10^{-3}$ and 1.7 $10^{-3}$ $sr^{-1}$ respectively on the retrieved BER. The Fig. 2 gives the histogram of BER after correction of the multiple scattering for each lidar profile. The mean value of the BER for the dust aerosol is close to 0.017 sr-1 with a standard deviation ~0.006 sr-1. The lidar ratio is then ~ 57±27 sr. This value could be compared to the results of Cattrall et al. [11] who studied the variability of the lidar ratio against the aerosol type from some selected AERONET measurements. Indeed, these authors found lidar ratio between ~25 and 60 sr for the dust aerosol.

## 6. DISCUSSION ON THE AEROSOL RADIATIVE IMPACT

The BER variability has a direct influence on the retrieved dust aerosol optical properties and thus on the determination of the aerosol radiative forcing at both the surface and the tropopause. To evaluate uncertainties on the retrieval of radiative forcings of the desert aerosols due to BER standard deviations we used the radiative transfer model Streamer developed by Key [12]. The direct radiative forcing is ~-40 (-46) and ~-8 (-18) W $m^2$ at the surface levels and at the tropopause, respectively, for desert (oceanic) surface. The mean heating rate in the aerosol layer is then close to 0.45 (0.40) K/day.

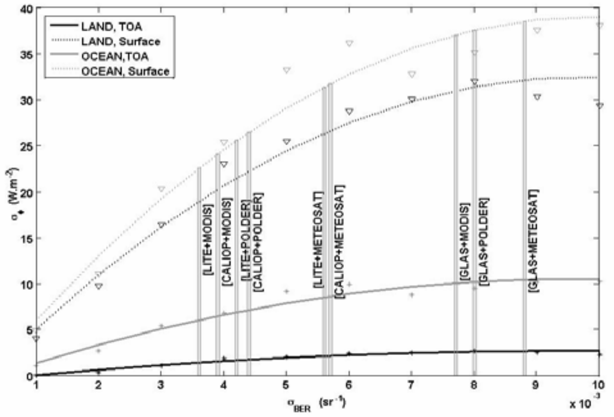


Fig. 3. Standard deviation of the dust aerosol radiative impact ($\sigma_{\phi}$) against the standard deviation on the BER ($\sigma_{BER}$) due to different instrumental synergies [10].

Fig. 3 show the standard deviations on the mean daily aerosol radiative forcing against the standard deviations on the BER. Relative errors are greater at the surface (~80% at the maximum) than at the tropopause (35-60% at the maximum). The BER standard deviations associated to various possible pairs of spaceborne lidar system and radiometer configurations were considered and the associated standard deviations on the dust radiative forcing are highlighted in Fig. 3. It is clear that for all the passive radiometers coupled with the GLAS lidar, standard deviations on the radiative forcing assessment are most important because of the weak signal to noise ratio associated with this instrument. In the near future, the CALIOP and MODIS synergy should yield the most accurate results on aerosol radiative forcing with standard deviations of ~ 20 (~24) and ~1.6 (~6.5) $Wm^{-2}$ at the surface and tropopause levels, respectively, for desert (oceanic) surfaces.

## 7. CONCLUSION

Such an approach is a first step in the perspective of the synergies that could be used for the new generation of spaceborne instruments as MSG, MODIS and POLDER onboard PARASOL. From a sensitivity study we have shown that the assessment of the BER may be carried out with standard deviations close to 0.003 $sr^{-1}$ (0.004 $sr^{-1}$) using the synergy between CALIOP and MODIS (CALIOP and PARASOL). Such a synergy may lead to a significant assessment of the dust aerosol direct radiative forcing at both the surface and the tropopause levels. Nevertheless, the uncertainty remains high (~50%) mainly because of both the signal to noise ratio of spaceborne lidar measurement and the uncertainty on the BER. A significant improvement can be obtained for the homogeneous aerosol layers which make it possible to average several coincident lidar and passive spaceborne observations in order to improve signal to noise ratio.

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