MSG IMPROVED CAPABILITIES FOR MARINE AEROSOL CHARACTERIZATION

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ABSTRACT

Aerosols have a significant contribution to the Earth radiative budget. MSG offers new capabilities to monitor aerosol transport over the Atlantic and the Mediterranean at high temporal and spatial resolutions, in particular Saharan dust from North Africa, biomass-burning aerosols from subtropical Africa and pollution plumes from Europe. We developed an inversion technique using MSG bands at 0.6 and 0.8 µm to estimate both aerosol optical thickness and Angström coefficient. The code is written in Fortran 95 and optimized for a fast processing of full-resolution MSG imagery, thus allowing to process long MSG time series. This inversion technique was applied to MSG slots 45, 49 and 53 (11:15, 12:15, 13:15 UT) of June 2003. The retrieved optical thicknesses and Angström coefficients are in good agreement with AERONET in situ measurements in the Atlantic and in the Mediterranean. Monthly mean maps of both parameters also demonstrate the potential of the method.

1. INTRODUCTION

Aerosols contribute significantly to the Earth radiative budget. Their concentrations have to be monitored at the global scale to develop and validate climate models that take into account the impact of these airborne particles. Because of the strong variability of aerosol sources, distributions and optical properties, high spatial and temporal monitoring is needed. Satellites are well suited for such a monitoring [1]. The new characteristics of SEVIRI onboard MSG make it an invaluable tool to study aerosols over the oceans. Daily images of the METEOSAT VIS band were used to monitor almost ten years of African dust transport over the Atlantic and the Mediterranean. The images were first calibrated [2,3] and a Look-Up Table (LUT) of TOA reflectances from radiative transfer simulations was used to retrieve the dust optical thickness [4]. This method was applied to the entire set of noon images of the ISCCP-B2 archive between 1983 and 1997. This unequaled data set enabled us to generate the first monthly climatology of African dust loads over the Atlantic and the Mediterranean and to show that the intensity of dust export is closely related to climate parameters such as the North Atlantic Oscillation and the Sahel drought [5,6].

The major shortcoming of this method is that a single spectral band does not allow to compute both aerosol load and aerosol optical properties, thus implying that the radiative transfer simulations of the LUT are made for a single aerosol model, whereas several types of aerosol are present in the marine atmosphere, each one with different optical properties and radiative impact in the solar spectrum. Contrary to METEOSAT, MSG has three narrow spectral bands in the solar spectrum (at 0.6, 0.8 and 1.6 µm) in addition to the wide HRV band. Our objective here is to use the two solar bands at 0.6 and 0.8 µm to retrieve the spectral signature of the aerosol reflectance and thus the type of aerosols (i.e. size distribution and refractive index) in order to generate maps of both aerosol optical thickness and type from MSG images. In particular, we endeavor to differentiate Saharan and Sahelian desert dust from subtropical Africa biomass burning aerosols and from pollution aerosols downwind of Europe.

2. METHOD

2.1 Radiative transfer computations

The signal measured in the solar spectrum by a space-borne sensor is the sum of the light backscattered toward the satellite by the ocean surface, the atmosphere molecules and the aerosols. The contribution of aerosols to MSG Top-Of-Atmosphere (TOA) reflectances is simulated in both 0.6 and 0.8 µm bands with the radiative transfer model 6S [7] for various geometries and 15 different aerosol optical thicknesses at 0.55 µm (λ). [7] was varied from 0 for an aerosol-free atmosphere, i.e. with only molecular and marine reflectances, to 2 for a very turbid atmosphere. The 6S model uses the up-to-date successive orders of scattering technique to compute the aerosol reflectance. It also takes into account the gaseous absorption in the atmosphere (mainly by O₃, H₂O and O₂) by using predefined atmospheric compositions. Here we used the US62 standard, which corresponds to an ozone content of 0.344 cm-atm and a water vapor content of 1.42 g.cm⁻². Note that we considered a “black” ocean, i.e., that the marine reflectance is equal to zero outside the sun glint area. Note also that the spectral integration of the various reflectances over the satellite band is performed with a step of 0.5 nm.
Aerosol optical properties in the Atlantic and the Mediterranean may vary widely depending on the size distribution and refractive index of the particles, which in turn depend on the source and nature of the aerosols. The Angström coefficient ($\alpha$) is an optical property that can be used as a proxy for the aerosol size distribution. $\alpha$ is computed from the spectral variation of $\rho$ between two wavelengths and is large (up to 2.5) for very small aerosols like sulfates from polluted areas and is low ($\approx$ 0) for aerosols containing large particles as desert dust. Here we define $\rho$ from the 0.6 and 0.8 \( \mu \)m bands. Both in situ and satellite measurements in the Mediterranean have shown that the Angström coefficient computed in the visible varies roughly between 0 and 2 [8,9].

To build our look-up table, we decided to use a set of 15 aerosol models with Angström coefficients ranging from −0.1 to 2.4. These models include the 12 models developed for the atmospheric correction of SEAWIFS imagery [10,11], which cover Angström coefficients up to 1.5. This set was complemented with three additional models of very small particles to cover the range 1.8 – 2.4 in Angström coefficient. These three models were derived from the tropospheric mode of [11] for a relative humidity of 0% for which the mean radius was decreased from 0.027 \( \mu \)m to 0.021, 0.017 and 0.015 \( \mu \)m to get an Angström coefficient of 1.8, 2.0 and 2.4, respectively. The major advantage of this set of models is that the spectral slope of the simulated aerosol reflectance, which is used to identify the best aerosol model, varies continuously, so that it is possible to interpolate the aerosol reflectance between two consecutive models without searching the whole set of models.

For each aerosol model (i.e., size distribution and refractive index), a LUT was made of TOA MSG reflectances at 0.6 and 0.8 \( \mu \)m computed with 6S for about 110000 different measurement geometries: 48 values for both solar zenith angle $\theta_S$ and viewing zenith angle $\theta_V$ (varied between 0 and 90°), and 49 values for the relative azimuth angle $\Delta\varphi$ between 0 and 180°.

### 2.2 Image processing

In terms of image processing, we followed approximately the same method as for METEOSAT [4]. The first step is to convert the numerical counts in TOA reflectances using the calibration coefficients presented by Y. Govaerts at the 2003 EUMETSAT Meteorological Satellite Conference in Weimar. The next step is to remove cloud-contaminated pixels over the ocean using the spatial variability of the TOA reflectance at 0.8 \( \mu \)m, aerosol plumes being much more homogeneous than clouds. We thus applied a simple threshold of 0.0045 on the standard deviation of the TOA reflectance computed on 3x3 pixels. An additional test removes the pixels located next to a cloudy pixel (as detected by the test on the local variance).

It is also necessary to remove pixels affected by sun glint. Wherever present, the specular reflection of the sun on the sea surface is so intense that it prevents from retrieving aerosol optical properties. The size of the contaminated zone depends strongly on the wind speed and direction, a piece of information that is not available within our processing. In order to avoid any possible sun glint contamination, we thus decided to discard all pixels with a “sun glint angle” (which characterizes the angular distance to the specular direction) lower than 30°. Finally, pixels with a too extreme geometry ($\theta_S$ or $\theta_V$ greater than 75°) are also discarded because they are out of the validity range of the 6S radiative transfer model.

The last step of the image processing is the inversion itself. It makes use of the LUTs that have been computed once and for all prior to the image processing. For the geometry of the pixel, the aerosol optical thickness at 0.55 \( \mu \)m is computed for each aerosol model by interpolating in the LUT the value that yields a theoretical TOA reflectance at 0.8 \( \mu \)m equal to the measured one. The LUT is further used to interpolate the corresponding theoretical TOA reflectance at 0.67 \( \mu \)m. This is done for the 15 aerosol models. The best solution (i.e., an aerosol model and an optical depth) is the one that minimizes the difference between the theoretical and the measured TOA reflectance at 0.67 \( \mu \)m. The results of this processing are output as maps of both the aerosol optical thickness and Angström coefficient, generated in two different formats : an “image” format (GIF files) and a “raw” format (8-bit binary files).

The developed computer code is written in Fortran 95, with some routines in C for the original image decoding. It has been optimized to enable the processing of a full resolution image (one slot at 3 km resolution at nadir) in less than five minutes on a standard mono-processor PC/Linux. This is fast enough to enable the processing of several slots per day for long periods of time: it takes about 24h to process one month of MSG data with 9 slots per day. Note that this performance is strongly improved as compared to what had been done before with METEOSAT.

### 3. PRELIMINARY RESULTS

Fig. 1 compares daily maps of aerosol optical thickness obtained using one single slot and combining the measurements of nine successive slots. The use of several images per day yields a significant improvement of the spatial coverage for three main reasons: (1) it enables to get rid of the sun glint contamination (located in the Gulf of Guinea in the single slot image); (2) it fills a large fraction of the cloudy areas where the cloud coverage is fractional (mainly in the tropics) because clouds are moving during the day; (3) it enables to process pixels that are not enlightened on one particular
slot (e.g., pixels on the edge of the Earth disk on the noon image). The daily map obtained using nine slots in Fig. 1 has a remarkable spatial coverage when compared to what is produced by orbiting sensors with comparable spatial resolution such as MODIS (1 km) or POLDER (6 km). This will clearly improve the quality of the weekly or monthly mean aerosol products and facilitate the physical interpretation of interesting aerosol events. Such an example can be seen in Fig. 1, which shows both the African dust plume over the Atlantic up to America and a transport of (likely) biomass burning aerosols from southern Africa.

It is interesting to note that the daily mean optical thickness within dust-contaminated regions is somewhat different from that retrieved from a single image (in the Persian gulf or in the western part of the Atlantic dust plume). This is likely due to the fact that the aerosol optical thickness may vary significantly during the day in regions close to the sources or where the wind is strong. It is however also possible that part of this diurnal variation of the optical thickness is artificial and related to the wrong assumption of particle sphericity when computing aerosol optical properties throughout the Mie theory [12].

Fig. 2 shows preliminary monthly mean maps of retrieved aerosol optical thickness and Angström coefficient for June 2003 using only three slots per day instead of the nine slots scheduled for the final processing. Aerosol optical thicknesses are consistent with those of the METEOSAT climatology [5]. The dominant aerosol transports show up clearly: African dust over the Atlantic, the western Mediterranean, the Red Sea and the western Indian Ocean; biomass burning aerosols south of the Gulf of Guinea. These two dominant aerosols are characterized by Angström coefficients of about 0.4 - 0.7 for mineral dust and of about 1.4 - 1.7 for biomass burning aerosols. Interestingly, the Angström coefficient map brings up additional information in regions where the optical thickness is small, such as the predominance of aerosols from likely pollution origin in the East Mediterranean downwind eastern Europe or the plume of likely biomass burning aerosols coming from Amazonia over the southern Atlantic. Note that the zone contaminated by the Sun glint does show up in these preliminary maps because of the restricted number of slots used.

4. VALIDATION

Direct measurements of the aerosol optical thickness at several wavelengths in the visible and the near-infrared at coastal Mediterranean and Atlantic stations by the AERONET network [13] were used to validate $t_\tau$ and $t_a$ retrieved from MSG measurements. Hourly level 2.0 (cloud-screened and quality-assured) sun photometer measurements at six stations (see Table 1) were available for June 2003. Because sunphotometers do not always have a channel at 0.55 $\mu$m, $t_\tau$ was linearly interpolated between the two basic bands at 0.44 and 0.67 $\mu$m to ensure the compatibility with MSG estimates. $t_a$ was computed directly using the measured aerosol optical thicknesses at 0.67 and 0.87 $\mu$m. In order to reduce the possible noise due to the diurnal variability, AERONET measurements taken between 10:00 and 14:00 UT only were averaged and used for the validation because we only considered MSG images taken at 11:15, 12:15 and 13:15 UT.

The comparison between MSG retrievals and sun photometer measurements was made by extracting $t_\tau$ and $t_a$ over the closest 3x3 pixel marine area distant of at least 5 km of the coast to avoid turbid water contamination. 77 coincident measurements were available for our validation. Fig. 3 shows the results of the comparison for the AERONET station located in Crete, in the eastern Mediterranean. As shown in Fig. 2, this region is of particular interest for aerosol studies because of the contrasted influences of Europe (pollution) and North Africa (desert dust). In addition, there is almost no cloud during summer over this region. In AERONET data, $t_\tau$ varied between 0.1 and 0.4 at this station during June 2003 and $t_a$ between 0.5 and 2.0. Fig. 3 shows a good agreement between MSG retrievals and ground-based measurements. The sensitivity of the MSG Angström coefficient is remarkable, even if it seems overestimated during the last week of June 2003; it clearly allows differentiating African dust ($t_a = 0.5$ on day 4) from others. The agreement is also good for aerosol optical thickness. The largest difference is for the African dust event of day 4, suggesting that none of our aerosol models is suitable for mineral dust study.

Fig. 4 summarizes the validation results for the six AERONET stations. Coefficients of the linear regressions show that there is no bias between the two datasets, and that the accuracy of MSG retrievals is satisfactory, mainly in term of optical thickness (about ±25%). The point with the largest discrepancy ($t_a = 0.17$ for AERONET and 0.62 for MSG) is from the Dahkla dataset and corresponds presumably to a dust plume that was transported over the ocean but not over the coastal AERONET station. The number of outliers in Fig. 4 is larger for $t_a$ than for $t_\tau$ likely because this parameter being computed as the ratio of $t_\tau$ at two wavelengths, it is highly sensitive to uncertainties on $t_\tau$ for low values (e.g., $t_\tau < 0.15$). Further analysis should confirm this hypothesis.
Fig. 1. Impact on the spatial coverage of the number of slots used per day to compute the daily aerosol optical thickness for June 7th, 2003. The left map has been computed with one single slot (12:00 UT) whereas the right map has been computed using nine slots (from 8:00 to 16:00 UT by step of 1 hr). Continents are in dark grey whereas masked marine pixels (either cloudy or contaminated by the sun glint) are in white.

Fig. 2. Monthly mean maps of the aerosol optical thickness (left) and Angström coefficient (right) for June 2003 as retrieved from MSG/SEVIRI images using three slots per day (11:15, 12:15 and 13:15 UT). Note that 5 days (June 15th to June 19th) of MSG data were not available by the time of this study. The East-West dissymmetry in the images is because MSG was shifted at 10°W in June 2003.
Table 1. AERONET stations available in June 2003 to validate MSG aerosol retrievals.

<table>
<thead>
<tr>
<th></th>
<th>Capo Verde</th>
<th>Dahkla</th>
<th>Azores</th>
<th>Forth Crete</th>
<th>Erdemli</th>
<th>Nes Ziona</th>
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<td>Longitude</td>
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<td>15.95°W</td>
<td>-28.63°W</td>
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<td>34.25°E</td>
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<td>23.72°N</td>
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<tr>
<td>P.I.</td>
<td>D. Tanré</td>
<td>H. Benchekroun</td>
<td>B. Holben</td>
<td>M. Drakakis</td>
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Fig. 3. Comparison of MSG retrievals with AERONET measurements at the Forth Crete station in June 2003 for both aerosol optical thickness $t$ (bottom) and the Angström coefficient $a$ (top). AERONET measurements are represented by opened symbols and MSG retrievals by closed symbols. Note that 5 days (June 15th to June 19th) of MSG data were unavailable by the time of this study.

Fig. 4. Comparison of the 77 coincident MSG and AERONET measurements for both aerosol optical thickness $t$ (left) and Angström coefficient $a$ (right). The slope of the linear regression is 1.0 for $t$ and 1.02 for $a$, and the correlation coefficient $r$ is respectively of 0.83 and 0.58.
5. **CONCLUSION**

MSG bands at 0.6 and 0.8 µm allowed us to develop an inversion technique to estimate both aerosol optical thickness and aerosol Angström coefficient by a best-match comparison of MSG spectral measurements and 6S pre-computed TOA reflectances. We applied this inversion technique to slots 45, 49 and 53 (11:15, 12:15, 13:15 UT) of all available days of June 2003.

Monthly mean maps of both parameters exhibit clearly the dominant aerosols, i.e., mineral and biomass burning aerosols, as well as the influence of pollution from Europe over the Mediterranean. A comparison with AERONET in situ measurements performed in the tropical Atlantic and in the Mediterranean shows that MSG retrievals have a relatively good accuracy for both optical parameters, even if the Angström coefficient retrieved from MSG shows significant dispersion.

The preliminary results presented here demonstrate the potential of MSG for the characterization of marine aerosols. They particularly evidence the benefit of using several MSG images per day instead of one single slot or of polar orbiter swaths. Thanks to the efficiency of our inversion code, we aim at processing nine MSG slots per day in full resolution over several months. The monthly mean maps generated will be compared to that obtained with an "aerosol-dedicated" sensor like POLDER-2, which has provided data from April to October 2003. We will also try to use the MSG 1.6 µm band within our inversion in order to likely improve the Angström coefficient estimates.

6. **ACKNOWLEDGEMENTS**

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7. **REFERENCES**


