

RETRIEVAL OF AEROSOL PROPERTIES FROM SEVIRI USING VISIBLE AND INFRA-RED CHANNELS.

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Abstract

This work is based on the optimal estimation aerosol retrieval algorithm (ORAC), developed at the University of Oxford and the Rutherford Appleton Laboratory, for the visible and near infra-red channels of ATSR and SEVIRI. The scheme has been used and validated in several projects including NERC GRAPE and ESA Globaerosol. Here the algorithm is extended to include the two SEVIRI infra-red window channels centred at 10.8 and 12.1 microns. The aerosol parameters we retrieve are optical depth (at 550 nm), effective radius and the effective altitude of aerosol layer.

DISORT (DIScrete Ordinate Radiative Transfer) radiative transfer code is used for the vis/nir channels and it takes into account atmospheric scattering and absorption. For the IR channels DISORT is used to compute the aerosol scattering, absorption and emission terms, which are combined with the clear-sky and surface contributions (themselves based on ECMWF data and RTTOV computations). The forward model uses an aerosol database of optical properties computed from different sets of published aerosol micro-physical properties (size distribution and refractive index). The IR channels are sensitive to large (effective radius \sim 1 μ m) aerosol particles (like desert dust), to surface temperature and to spectral emissivity.

In this work we give some preliminary results for a Saharan dust plume in March 2006. The retrieval is shown to be sensitive to the consistency of the assumed IR and vis/nir refractive indices: not all aerosol models which result in reasonable fits to the measurements in the vis/nir range are capable of simultaneously fitting IR radiances. This finding can be used to better characterise the observed aerosol by discriminating between different aerosol types. The set of aerosol optical properties that can simultaneously fit both VIS, NIR and IR measurements are presumably the best set to use for monitoring desert dust events and modelling their radiative effect in both the short and long-wave.

The addition of the IR channels allows us to follow and quantify desert dust events over bright surfaces. SEVIRI aerosol optical depths (AOD) are compared with MISR and Aeronet data giving correlation between the dataset 0.69 and 0.87 respectively.

INTRODUCTION

Remote sensing of aerosols from satellite is the most convenient tool for providing global information on aerosol spatial and temporal distributions.

Visible nadir algorithms fail for aerosol retrieval over bright surfaces like the Sahara desert because it is not easy to distinguish the aerosol signal from the surface reflectance (MODIS, Levy et al. 2007, Remer et al, 2005; AVHRR, Geogdzhayev et al, 2002; SEVIRI, Thomas et al. 2007; MERIS Santer et al. 2000; GOME, Carboni 2006).

Aerosol retrieval over a bright surface is made possible by particular instrument characteristics such as multi-angle observation (MISR, Martonchik et al, 2004; AATSR, Grey et al 2006) ; measurements in the UV spectral region, (TOMS, Torres et al, 1998; OMI Veihelmann et al, 2007); or polarization measurements (POLDER, Deuze et al, 2001). All these instruments are, at present, on board of polar platform, and thus not permit the global monitoring of aerosol evolution during the day.

On board of Meteosat Second Generation (MSG) geostationary satellite we have the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI). It gives images with a spatial resolution of 3 km,

every 15 minutes. SEVIRI has 12 channels in the 0.6-14 μm range. In this study we use three VIS-NIR + two IR channels centred at 0.640, 0.809, 1.64, 10.78, 11.94 μm .

The SEVIRI IR channels are affected by gas absorption such as water vapour. So retrieval using IR channels is possible only using external information such as ECMWF data (of gas and temperature profiles, and a priori surface temperature T_s)

There are some desert dust retrievals using 'only' IR measurements (Zhang et al 2006, Pierangelo et al 2004, DeSouza-Machado 2006) but simultaneously using both IR and visible near infrared with the optimal estimation algorithm allows us to retrieve aerosol optical properties in an optimal way, giving more importance to the visible channel over oceans and more importance to IR over bright surfaces.

ORAC¹ AEROSOL PROCESSOR

The Oxford-RAL retrieval of Aerosol and Clouds (ORAC) scheme (Thomas et al 2007, Poulsen et al 2007) is a retrieval scheme developed for determining aerosol properties from satellite borne radiometers such as the ATSR and SEVIRI instruments. The ORAC forward model is sensitive to aerosol size, chemical composition, and shape, as these characteristics determine aerosol radiative behaviour. ORAC is being used in the NERC GRAPE² and ESA Globaerosol³ projects. Visible reflectance (at each wavelength) is approximated as:

$$(1) \quad R = R_{BD} + \frac{T_B T_D R_S}{1 - R_S R_{FD}}$$

where R_S is the Lambertian surface reflectance, T_B and T_D are respectively the atmospheric transmission of the incoming beam and the atmospheric transmission of the diffuse reflected radiance, R_{BD} and R_{FD} are respectively direct bidirectional reflectance of the atmosphere and atmospheric reflectance of diffuse reflected radiance. Eq. 1 allows us to separate the contributions of the surface from the atmosphere into the calculation of the top of atmosphere radiance.

Atmospheric reflectances and transmittances are precomputed (for every aerosol type) in look-up-tables (LUTs) as a function of aerosol optical depth, aerosol effective radius and geometric conditions. Aerosol optical properties and microphysical characterisation of aerosol are important factors in these computations as will be explained. Atmospheric radiative transfer is modelled using DISORT with 32 layers, 60 streams, δ -M approximation and MS methods (considering the first 1000 Legendre moments as the exact atmospheric phase function). Aerosol is placed only at height levels appropriate for the aerosol type. The atmospheric layer properties of optical depth, phase function and single scattering albedo are obtained by considering the properties of the aerosol particles and local gases. Absorption optical depth for the local gases in the visible and the near infrared are obtained from Moderate Resolution Transmittance Code (MODTRAN).

We use an Optimal Estimation (OE) approach (Rogers, 2000) to extract information from all channels simultaneously. The OE method allows us to characterise the error in each parameter in each individual observation (or 'pixel') under the assumption that the aerosol observed is consistent with the modelled aerosol. A second diagnostic (the solution cost) indicates whether in fact this assumption is true. The OE framework also allows us to use any prior information on the pixel observed. In terms of retrieved products we currently only have significant a priori information on surface albedo, however, all the clear atmospheric (i.e. non-aerosol) effects on the IR measurements are derived from prior information in the form of NWP profiles (ECMWF). The MODIS albedo data set is used to provide the first guess of the surface albedo over land (Wanner et al, 1997), over ocean we consider the model explained by Sayer (2007). The surface albedo is retrieved by first assuming an albedo spectral shape for the 0.67, 0.87 and 1.6 μm channels. Over land this spectral shape is available from the MODIS albedo product. The retrieval searches for the solution with the lowest cost by varying the albedo in the 0.67 μm channel and keeping the respective ratios of all other channels constant.

The OE allows for the simultaneous inversion of all products using all measurements and a weighted a priori with appropriate levels of confidence. The retrieved state includes: aerosol optical depth (at 550 nm), aerosol effective radius and surface reflectance (at 550 nm).

IR FORWARD MODEL

Extending the retrieval to mid-IR adds significant information for large aerosol (effective radius $R_{eff} \sim 1 \mu m$), as is the case of desert storm, maritime aerosol and in some cases to volcanic ash. The addition of the 2 infrared channels enhances sensitivity to aerosol vertical distribution, temperature profile and surface temperature.

In the IR forward model we consider the different contributions to the signal using different parameters for atmosphere (gas absorption and emission) and aerosol. Aerosol are modelled as a pure aerosol single layer at a variable height (pressure) with atmosphere above and below the layer.

The infrared radiance measured by satellite is modelled as the sum of 4 contributions: (i) the radiances emitted by the aerosol layer and transmitted through the atmosphere above, (ii) the down-welling radiance from the atmosphere above reflected by the aerosol layer and transmitted by atmosphere above, (iii) the radiance emitted by the atmosphere above, (iv) the radiance emitted by the atmosphere below and by the surface, and transmitted through the aerosol layer and the atmosphere above.

We use the subscript 'l' (layer) for aerosol. For other atmospheric contributions we divide it into two parts below ('bl') and above ('al') the aerosol layer.

We consider the following parameters. Above aerosol layer: down-welling radiance I_{al}^{\downarrow} ; up-welling radiance I_{al}^{\uparrow} ; the transmittance T_{al} . Aerosol layer: reflectance R_l ; emissivity ϵ_l ; transmittance T_l ; Plank radiance B_l at aerosol layer temperature. Below aerosol layer: up-welling radiance I_{bl}^{\uparrow} ; transmittance T_{bl} . Surface contribution: surface emissivity ϵ_s ; Plank radiance B_s at surface temperature.

Excluding multiple reflection between the aerosol layer and surface reflectance, we can write (for every wavelength):

$$(2) \quad I^{\uparrow} = B_l \epsilon_l T_{al} + I_{al}^{\downarrow} R_l T_{al} + I_{al}^{\uparrow} + I_{bl}^{\uparrow} T_l T_{al} + B_s \epsilon_s T_{bl} T_l T_{al}$$

Where the aerosol layer parameters (ϵ_l , R_l , T_l) are precompiled in LUTs. Other atmospheric parameters (transmittances, radiances above/below aerosol layer going up/down) are computed with RTTOV using ECMWF atmospheric profiles.

The retrieved state with IR include: aerosol optical depth (at 550 nm), aerosol effective radius, surface reflectance (at 550 nm), surface temperature and effective pressure of the aerosol layer.

AEROSOL OPTICAL PROPERTIES

The nadir satellite signal is influenced predominantly by scattering, in both the visible and the near infrared spectral regions (SEVIRI channels 1,2,3), and by the total extinction in the infrared (SEVIRI ch. 9 and 10). For both spectral ranges (VIS-NIR and IR), the aerosol optical properties (spectral extinction coefficient, single scattering albedo and phase function) of each aerosol type are calculated using Mie scattering (Grainger et al., 2004) and external mixing. Every aerosol type is formed from up to 4 aerosol components, and every component is characterized by: (1) mode radius and spread of a log normal size distribution by number; (2) spectral refractive index. These properties are calculated for the central wavelength of each channel across a range of effective radii from 0.01 to 10 μm . Two main assumptions are made during this step:

- That the radiative properties of the aerosol are constant across the width of each instrument channel. As the features of aerosol extinction spectra are very broad in comparison with gas features this is a reasonable approximation.
- Assumptions must be made in determining both the form of the aerosol size distribution and how its shape varies with changing aerosol effective radius. At present the preferred option is that the component's size distribution stays fixed, while the mixing ratio between components changes in order to produce the desired effective radius. This means that in order to increasing effective radius we increase the number density of the larger modes of the distribution (or even create of new large mode) at the expense of smaller modes.

REFRACTIVE INDEX PROBLEM

Retrievals in the IR region are complicated by the uncertainties in the aerosol spectral refractive index. Looking at the literature, the real and imaginary part of the refractive index for desert, mineral and sand components have different values around 11 and 12 μm .

We chose to study the desert plume of 8 March 2006, assuming 3 different aerosol refractive index datasets:

- 1) OPAC dust model (Hess et al., 1998)
- 2) Dust-like aerosol (D'Almeida et al., 1991)
- 3) Saharan dust model from Peters (2007).

Fig.1 presents some retrieved parameters, without any omission of data for quality control. The red pixels in the first box (AOD with only vis-nir) are presumably cloudy pixels that push the retrieval to the extreme of the LUTs (AOD=5, visualized as red). The columns on the right represent the retrieval with the addition of the infrared channels obtained with the three different spectral refractive index datasets.

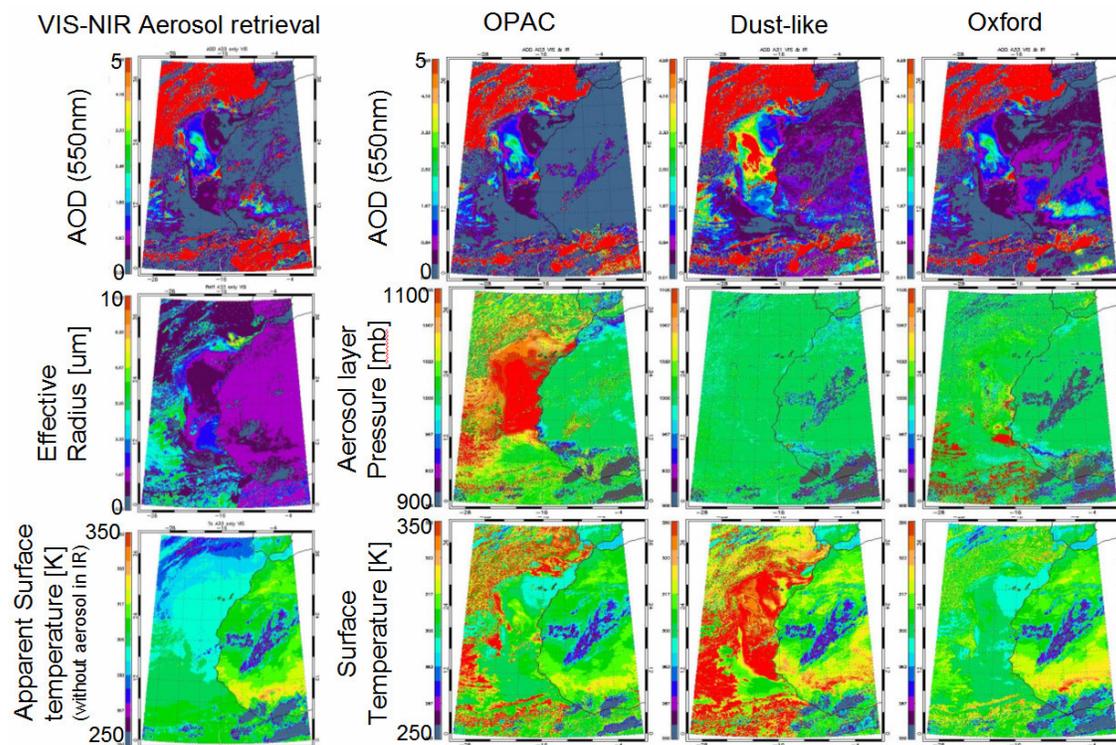


Figure 1: Aerosol retrieval results for 8 March 2006. In the left column are the AOD and Reff retrieved using vis-nir channels, the third box is the surface temperature obtained from IR channels considering a clean atmosphere (without aerosol). The 3 columns on the right represent the retrieval with the addition of the IR channels obtained with the 3 different spectral refractive index datasets (as indicated above). It is possible to note that the first 2 of the 3 retrievals with IR produce unrealistic value for aerosol layer altitude (pressure) and surface temperature respectively.

The first two of the three aerosol models chosen are incapable of fitting the SEVIRI measurements with a physically realistic aerosol and surface state. Of the models used, the new refractive indices measured by Oxford in the RAL Molecular Spectroscopy Facility, provide the most consistent representation and we chose this last one for the following analysis.

However there remain discrepancies, particularly in the spectral shape of the fit-residuals, that indicate the need to further improve the aerosol infra-red characterisation.

CASE STUDY: DESERT PLUME, MARCH 2006

In Fig.2 we present the results of the retrieval extended to the use of the two IR channels, applied to a desert dust event on March 2006. It is possible to observe the AOD in the different SEVIRI images

from 5 to 16 March 2006. The desert storm initially started in Algeria on 6th March and spread out south over the Sahara desert and west over the Atlantic ocean in the following days. Colours bars represent AOD from 0 to 2 in violet to red, the black point are AOD greater then two. Note that the desert plume is continue over ocean and land.

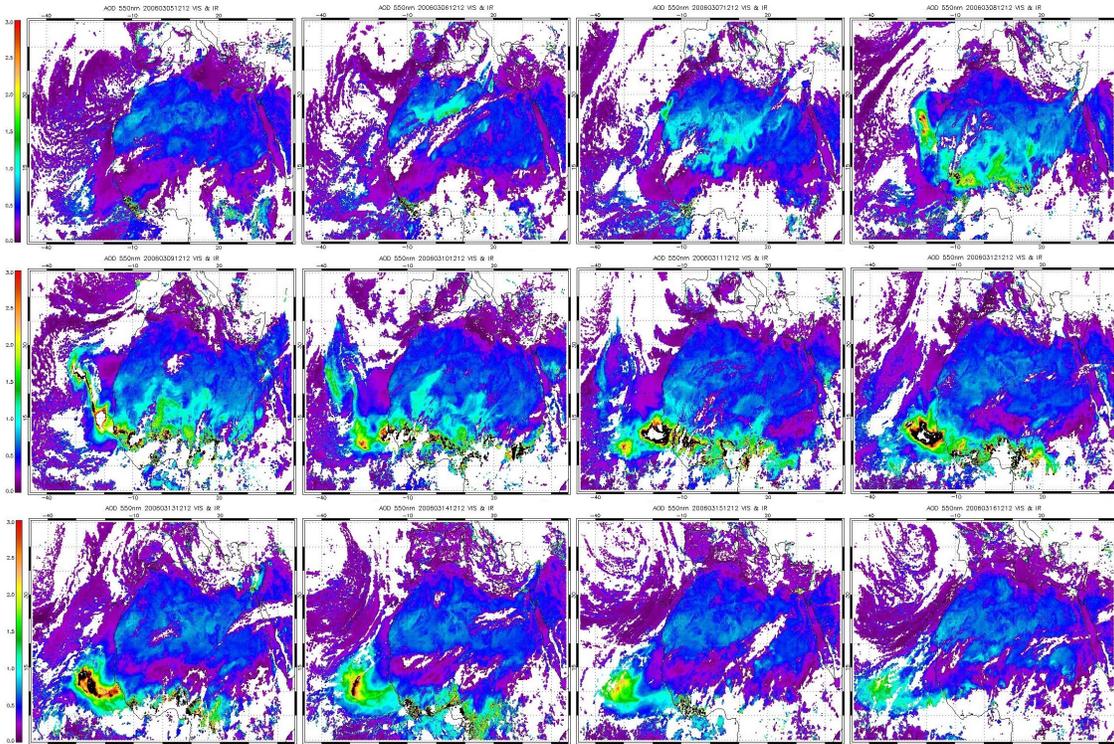


Figure 2: Aerosol optical depth (AOD) at 550nm from 5th to 16th March 2006 (from right to left and top to bottom), retrieved using both visible and infra-red channels. SEVIRI data at 12:12 UTC. Colours bars represent AOD from 0 to 3, AOD larger then 3 are represented by black.

COMPARISON WITH MISR DATA

We made a preliminary comparison, for the period from 5th to 10th March, between MISR AOD (level 3 daily AOD, from NASA Earth Observing System Data Gateway) and SEVIRI AOD (both at 550 nm) retrieved adding IR channels. For SEVIRI retrieval only images at noon are considered in this analysis. The SEVIRI retrieved AOD are averaged to match the given MISR spatial resolution. The quality control applied to SEVIRI data are: cost function < 15; $0.01 < \text{AOD} < 4.9$; $\text{Reff} < 7\mu\text{m}$. Cut of data depending on Eumetsat cloud mask is not applied because it will remove the strong desert events. Fig. 3 shows one example of the SEVIRI data average and the corresponding MISR data. Similar features over ocean and over desert are seen by MISR and SEVIRI. However SEVIRI overestimates the AOD over north Africa (presumably still affected by some errors modelling the surface). Fig. 4 shows the density plot for the same region as Fig.3 ($0 < \text{lat} < 40$, $-30 < \text{lon} < 40$ deg.) for the all period. Different colours (in logarithmic scale) correspond to different numbers of points in each box. There is a good correlation (0.69) between the two data sets with good agreement in correspondence of high AOD. It is possible to identify a region of pixels (corresponding to the north African region as seen in Fig.3) where SEVIRI AOD overestimate the low aerosol AOD (clean scenario) of 0.5. This is mostly a consequence of poor knowledge of either surface emissivity or reflectivity.

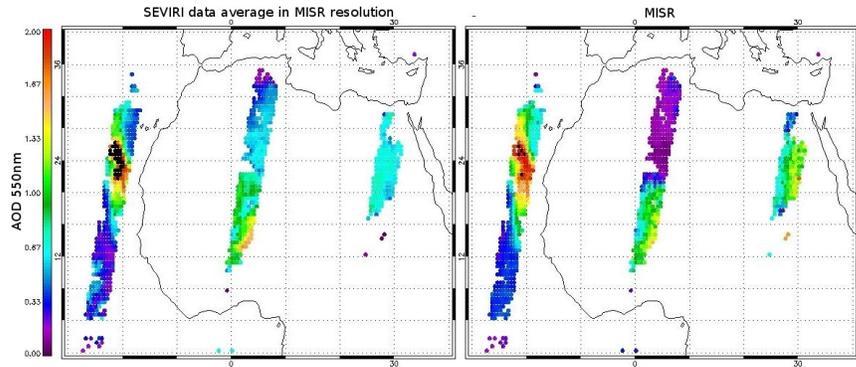


Figure 3: Example of SEVIRI

data re-sampled at MISR resolution (left), compared with the MISR data (right).

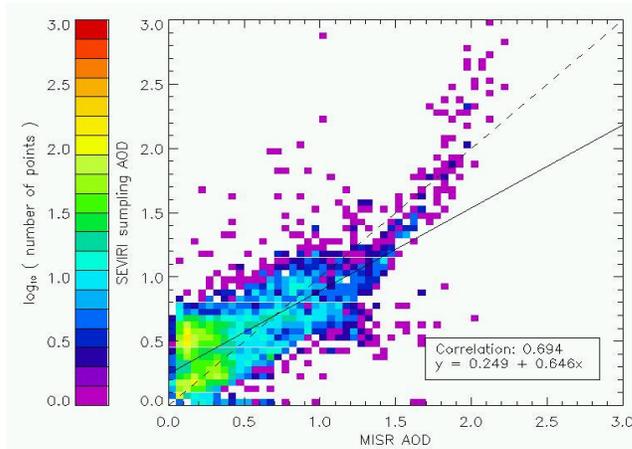


Figure 4: Density plot of AOD SEVIRI vs. MISR for the region 0:40 Lat. and -30:40 Lon. for the period 5-10 March 2006.

AERONET COMPARISON

For the period 5-20 March 2006 we made a comparison with AERONET level 2 ground data (Holben et al 1998), following the Globaerosol criteria (Poulsen et al. 2007). To compare point measurements from the ground with spatially averaged satellite data, both taken at slightly different times, we adopt the approach of Ichoku et al. (2002) which tackles the problem by assuming the spatial and temporal variability of the two datasets is correlated (through winds). We consider all the SEVIRI measurements within a region of 20 km from the Aeronet site and all the Aeronet measurements within 30 min from the satellite measurement. The standard deviation of both the SEVIRI and AERONET optical depth at 550 nm must be less than 0.15, this measure is adopted to remove cases which are likely to be cloud contaminated. At least four points must enter into the spatial mean for SEVIRI and the temporal mean for AERONET. The mean satellite and AERONET AOD values that respect these criteria are directly compared. Fig. 5 presents the scatter plot SEVIRI versus AERONET AOD at 550 nm for the region 0:40 Lat. and -30:40 Lon. Different symbols correspond to different Aeronet sites as indicate in the legend at the side. The slope of the fit shows a systematic underestimation of a factor of nearly 2 between SEVIRI AOD and Aeronet: note that this underestimation is not present in the previous comparison with MISR data. The correlation between SEVIRI and AERONET AOD is very good (0.87).

Fig 6 presents the same AOD set (SEVIRI in black and Aeronet in brown), but separately for each site, as function of the days of March 2006. Note that, in general, the SEVIRI data follows the same behaviour, as function of day, as Aeronet measurements. Instead in the North Africa region (like Tamanrasset) SEVIRI overestimate the AOD as previously identified in the comparison with MISR data.

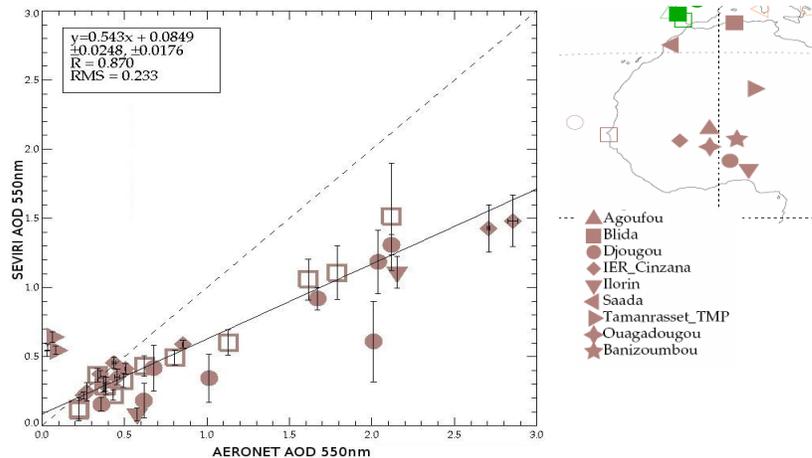


Figure 5: SEVIRI AOD vs. AERONET AOD at 550nm. Different locations are represented with different symbols as indicated in the legend.

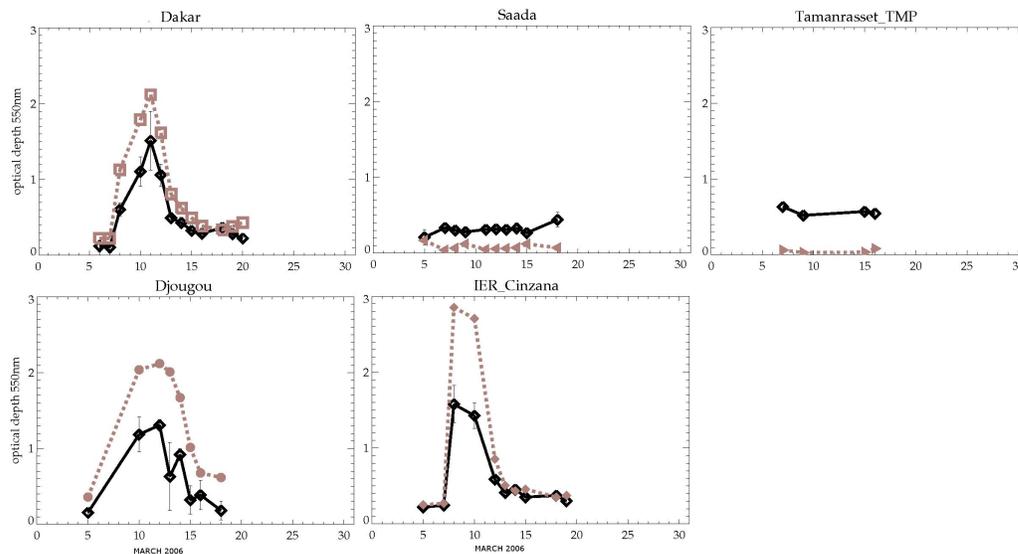


Figure 6: SEVIRI AOD (in black) and AERONET AOD (in brown) at 550nm vs the day of March on the x axis for the different Aeronet sites. The same data is present at Fig.4.

CONCLUSIONS

Results have been presented from new optimal estimation retrievals which simultaneously fit SEVIRI visible, near-ir and mid-ir radiances. The analysis is focused on a desert dust case study for which the IR channels add useful information to the solar channels by adding sensitivity over the bright desert surface and information on aerosol layer height.

It has been shown that results are dependent upon the assumed spectral refractive index of desert dust. Indeed the optimal estimation method is confirmed to be a valuable tool for testing the consistency of aerosol optical models and observations. Two of the three aerosol models chosen are shown to be incapable of fitting the SEVIRI measurements with a physically realistic aerosol plus surface state. Of the models used, the new refractive indices measured by Oxford in the RAL Molecular Spectroscopy Facility provide the most consistent representation. Using this set of optical properties it is possible to follow and quantify the desert dust events over bright surfaces with SEVIRI data. The comparison with others satellite (MISR) and ground (Aeronet) data show the success of the method (quantified with the high correlation coefficient). However, there remain discrepancies that show the need for future improvement of the characterization of the surface, and of aerosol in the infrared region.

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1. ORAC algorithm: <http://www.atm.ox.ac.uk/project/orac>
2. GRAPE project: <http://www.atm.ox.ac.uk/project/grape>
3. Globaerosol project: <http://www.globaerosol.info>