ABSTRACT

Over land, the aerosol remote sensing is based on the observation of Dense Dark Vegetation (DDV) and this concept is applied on MERIS with a spectral index (ARVI, Atmospherically Resistant Vegetation Index) to detect the DDV and the use of the bands at 412, 443 and 670 nm to characterize the aerosols. The aerosol size distribution is assumed to follow the Junge law while the aerosol refractive index is set to 1.44. The aerosol product consists on the aerosol optical thickness (AOT) at 865 nm and on the spectral dependence of the aerosol path radiance ($\varepsilon$ coefficient which is the ratio of the aerosol reflectance at 765 nm to that at 865 nm). The validation exercise is mostly based on the use of ground based optical measurements from the AERONET network. A classical validation of the aerosol product is conducted using the extinction measurements. A deeper validation is done in order to investigate the different assumptions used in the aerosol remote sensing module by: (i) using the ground based measurements to validate the DDV reflectance model. Atmospheric correction will be done, including the aerosols, to derive DDV reflectances for comparison to standard values. (ii) using the ground based measurements to validate the choice of the Junge size distribution by comparing the simulated radiances with this model to the measurements in the principal plane. The AOT at 865 nm is badly retrieved because of the inaccuracy of the DDV reflectance model in the red whereas the AOT at 443 nm is in good agreement with AERONET data and accuracy is comparable to what is achieved by MODIS over comparable sites. The Junge size distribution is well adapted for the representation of aerosols optical properties. The main algorithm improvement we recommend consists in introducing a dynamical DDV reflectance model that is a reflectance which varies with the ARVI of the target. Under clear sky conditions, the surface pressure is a level-2 MERIS product based on a two band ratio between 761.75 nm and 753 nm. This ratio is first corrected from the coupling between scattering and absorption to get the oxygen transmittance $T_{O_2}$. $T_{O_2}$ is pre computed versus the air mass $m$ time $P$ to simply derive $P$ from look up tables. The validation of the product itself is done by comparison to the barometric pressure collected from ECMWF and Digital Elevation Model attached to the MERIS product.

1. INTRODUCTION

Aerosol remote sensing over land from space is a difficult task because of the high reflectivity of Earth compared to the aerosol scattering signal in the back-scattering region. The technique chosen for MERIS relies on the well known Dark Dense Vegetation (DDV) concept recently generalized to the dark target concept for MODIS. The idea is to detect dark and stable targets whose reflectivity is known accurately with a simple and reliable method. For MERIS the choice was to use the Atmospherically Resistant Vegetation Index (ARVI) for detecting DDV pixels whereas MODIS team uses the capability to observe in the near-infrared at 2.1 $\mu$m for detecting dark target. In all of these techniques the two main sources of uncertainty are the accuracy of the reflectance model of the target and the aerosol models used for the computation of the aerosol scattering functions. In the case of MERIS, 20 biomes have been represented with the spatial and temporal variations of the DDV concept over the globe. For each biome a set of Look Up Tables (LUTs) has been generated that gives the DDV Bidirectional Reflectance Function (BRF) and the coupling terms between the DDV and the atmosphere. From these primary LUTs, secondary ARVI thresholds LUTs have been generated using the following formula:

$$ARVI = \frac{\rho_{\text{NIR}} - \rho_{\text{rh}}}{\rho_{\text{NIR}} + \gamma (\rho_{\text{rh}} - \rho_r)}$$

with

$$\rho_{\text{rh}} = \rho_r - \gamma (\rho_h - \rho_r)$$

where $\rho_{\text{rh}}, \rho_r$ and $\rho_{\text{NIR}}$ are reflectances, corrected for molecular scattering and gaseous absorption, observed respectively in the blue, red and near-infrared channels (443, 670 and 865 nm) and $\gamma$ was set to 1.3, a value that reduces sensitivity of ARVI to aerosol amount. ARVI thresholds have been computed for DDV and an aerosol layer with a given optical thickness and a given aerosol. The aerosol characterisation is based on standard aerosol models. For MERIS the 12 models used initially for POLDER aerosol remote sensing over land. They are defined by 4 values of the Angström
coefficient $\alpha$ (0.0, 0.5, 1.0, and 1.5) and 3 values for the real part of the refractive index $m$ (1.33, 1.44 and 1.55). The value $\alpha=0$ corresponds to large particles such as Saharan dust over arid region and great values of $\alpha$ correspond to small particles such as smoke particles. At the present time a reference to aerosol climatology is mandatory to set the aerosol refractive index. Optical thicknesses $\tau_\alpha$ in the red and in the blue are retrieved for each Angström coefficient. Finally, the model for which the Angström coefficient is the closest to the one obtained from the $\tau_\alpha$ retrieval is chosen. Then the aerosol level 2 product is calculated, that is the aerosol optical thickness in the near infrared $\tau(865\text{nm})$ and the $\varepsilon$ coefficient which has the same meaning that the one retrieved over ocean (ratio of the aerosol reflectance between the red and the near infra-red).

We present here the first results of the validation of MERIS aerosol product we obtain in 2003 using the AERONET network measurements. After the dataset description, a first part is dealing with the direct comparison of MERIS level 2 products with AERONET coincident data. Then we assess the robustness of the DDV detection with the ARVI threshold and show how to discard false DDV pixels. In a third part we demonstrate that the Junge Size Distribution is well suited to represent aerosol optical properties and thus that the choice of this particular size distribution does not affect the aerosol product accuracy. Finally we give some examples of the main problem affecting the aerosol product, i.e. the variation of the DDV reflectance with ARVI whatever the DDV model or the season. The overall approach for a correction of this effect is discussed and some recommendations for algorithm improvements are given in the final section.

2. DATA

2.1 AERONET

The AERONET database provides continuous monitoring of the aerosols columnar optical properties and also inverted microphysical parameters for various sites around the world (see Table 1 for the selected stations). We selected some representative sites with the following criteria:
- Getting a high number of coincident data with MERIS overpass.
- Covering various biome types and density to verify the robustness of the DDV concept.
- Covering various aerosol types to validate the aerosol models used in the MERIS level 2 processor.

We started by downloading the Aerosol Optical Thickness (AOT) product for each processing level, i.e., 1, 1.5 and 2 for the direct comparison with the MERIS aerosol product. For the validation of the aerosol model, we fetched the sky radiances in the solar principal plane (PPL). Level 1 data in AERONET terminology correspond to raw data, level 1.5 correspond to automatically cloud screened data, and level 2 correspond to quality assured data with the final calibration applied. For this study, we only use level 1.5 and 2 data. For the AOT in the visible, the accuracy is claimed to be less than 0.01 whereas the radiances should be calibrated to better than 5%.7

2.2 MERIS

We get Reduced Resolution level 1b MERIS data via a routinely ftp pull protocol on the GKSS server since end of 2002 and Full Resolution level 1b via regular mail. Up to now more than 1000 images have been archived in our database. The quality of the data is excellent. The only problem is that we do not have any match-up for few sites such as Oostende, Lille, Egbert, Ouagadoucou or Kanpur, thus undersampling the African and Asian DDV and aerosols models. A breadboard of the MERIS algorithm has been developed for validation purposes and mainly to derive level-2 products from these level-1B data. It follows the latest available version of the DPM (DPM i6r1 of 28 March 2003, PON-TN-MEL-GS-0006) but it is also able to include several new features and to provide more outputs such as the optical thickness at 443nm and the Angström coefficient. MERIS level 2 data have been also collected. Till now, more than 250 images are available for this study but they unfortunately don’t cover all the measurement sites.

3. SURFACE PRESSURE VALIDATION

The surface pressure reference used in this study for validation has been built using data attached to the MERIS L1B image, i.e. the pressure at the sea level from ECMWF and the surface elevation from a DEM. Those data are given every 16 (respectively 64) pixels in reduced resolution mode (respectively full resolution). The atmospheric pressure is supposed to decrease exponentially with a scale height of 8.34 km,

$$P_{ref} = P_{ECMWF}(z=0) \exp(-z_{DEM}/8.34)$$

This choice was made for having the largest amount of “ground truth” data covering a wide range of surface reactivity, elevation, roughness and air masses. The study was performed for 4 MERIS L1B image acquired in September 2003 over Europe, Amazonia and North America. The pressure difference images ($P_{O2}-P_{ref}$) are given in Figure 1. High values indicate the presence of clouds not detected by the current version of the cloud detection algorithm. Strong negative values correspond to regions where the O2 derived pressure is not well retrieved, mainly
mountains. This effect is significantly reduced when we use a high resolution DEM (1km like GLOBE for example, not shown here). In Figure 2 is reported the histograms of the pressure difference for the 4 images and for cloudless pixels. The are well fitted by a gaussian curve with a standard deviation of 18 hPa. Some scenes exhibits some small bias (d, 10hPa) whereas another one seems still contaminated by thin clouds and aerosols (c, 30 hPa and small scale noisy pattern).

Fig. 1: Surface pressure difference images, DEM low resolution. A mask for water pixel (cyan) and for cloud pixels (white) is applied.
Fig 2: Histograms of difference between oxygen derived surface pressure and barometric pressure corrected from terrain elevation for land pixels of images in Fig. 1.

4. AEROSOL PRODUCT VALIDATION

4.1 Methodology
The validation of the aerosols products retrieved from MERIS is mainly based on the comparison with the products derived from the ground based CIMEL instruments of AERONET. These data are archived in a data base. The parameters of high importance in regards with this work package are the aerosol optical thickness given at several wavelengths and the Ångström coefficient. The comparison between MERIS and ground based measurements is not straightforward because of the co-location problem. The so-called co-location problem comes from the comparison of a spatial measurement made at one moment (as for a satellite) with temporal measurements made at one location (time series). Comparison is then possible if, at least, one CIMEL measurement is performed within an interval $\Delta T$ of 30 minutes around the satellite overpass time $t_0$. Different values of this interval can easily be implemented in the data base. Finally if during this interval of time more than one measurement is found, the averaged value and the standard deviation are calculated.
The comparison becomes also trickier because aerosols properties over land can not always be retrieved for every pixel. Pixels must be cloud free and must reflect poorly (classified as DDV). To increase the number of possible comparison, aerosol products over a station is given for areas of different sizes. The size of the area is given by $\Delta X \times \Delta X$ where $\Delta X$ can be equal to 10 or 100 pixels. For each area, the mean value and the standard deviation of the aerosol product is calculated. Until now the data base is composed of MERIS and CIMEL data for each selected site and for the period from October 2002 to beginning of October 2003.

4.2. Comparison between AERONET and MERIS

4.2.1 Level-2 products

Figure 1 shows the optical thickness as derived from AERONET at 865 nm as a function of the optical thickness as retrieved from MERIS-L2 averaged over respectively 100x100 and 10x10 pixels. Errors bars in the plot are spatial and temporal standard deviations. Results are not correlated at all at the scale of 10 pixels. Even if a weak correlation can be found at the larger scale; results from MERIS are not in agreement with AERONET measurements. MERIS retrievals tend to be greater (from a factor 3-4 on average) than AERONET optical thickness. The spatial variability of the retrieved optical thickness is very high. Results are not significantly better when we reject cases with high cloud contamination and low DDV pixels presence (not shown). The Epsilon coefficient (ε) can be compared with the Angström coefficient which is a product from AERONET. Figure 2 illustrates the lack of correlation between the Angström coefficient and the Epsilon coefficient.

4.2.2 Aerosol optical thickness at 443nm

Accepting only cases with at least more than 1% identified as DDV, AERONET optical thicknesses at 440 nm are correlated with MERIS optical thicknesses at 443 nm (Figure 3). Results are significantly better at the scale of 10x10 pixels. The slope of the linear regression is $0.98 \pm 0.16$ taking into account spatial and temporal variability)) with an intercept of $0.018 \pm 0.041$ with an acceptable correlation factor of 0.76 whereas, at 100x100 pixels, the slope is 1.24 ($\pm 0.32$) with an intercept of $0.014 \pm 0.080$ and a correlation factor of 0.80. Better results at the smaller scale are explained by the effect that the pixels close to the station are more representative of the ground based measurements. Figure 3 contains more match-ups since all level 1B archive was processed whereas in figures 1 and 2 only official level 2 products were analysed. These results are comparable to those obtained with MODIS as shown in Figure 4.

![Fig. 2: Optical thickness at 865nm as derived from CIMEL (AERONET) versus the optical thickness retrieved from MERIS level-2 images and averaged over an area of 100x100 pixels (a) and 10x10 pixels (b) around the AERONET sites.](image-url)
5. DDV DETECTION

5.1 Spatial coverage

The main limitation of the ARVI method, at least in its nominal version, is to select only very dark targets which are rare and subject to strong seasonal variation, depending on location. In figure 7 are plotted typical DDV spatial coverage versus time for 2 different biomes, i.e. equatorial forest and european forest. For Surinam the coverage is sufficient and stable along the year. It enables the monitoring of aerosols background level in the image whatever the date. For Rome, it is only the case in end spring and summer.

5.2 Detectability

ARVI is slightly dependent upon the aerosol loading, with a decrease when the AOT increases. Consequently DDV detection is limited when the atmosphere is very turbid. An example of this effect is given in figure 8 where we show AOT maps derived from MERIS and MODIS for a close coincidence over Amazonian forest in July 2003. MERIS and MODIS are in good agreement for the region where the aerosol loading is moderate but MERIS fail to capture the large forest fire plumes because no DDV is detected there.

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Fig. 3: Angström coefficient derived from AERONET versus the Epsilon coefficient retrieved from MERIS level-2 images and averaged over an area of 100x100 pixels (a) and 10x10 pixels (b) centred around the AERONET sites.

Fig. 4: Optical thickness at 440nm from AERONET versus optical thickness at 443nm from MERIS level1B images. Only cases with more than 1% of the pixels flagged as DDV are kept to compare with MODIS study. MERIS optical thickness is averaged over an area of 100x100 pixels (a) and 10x10 pixels (b) centred around AERONET sites.

Fig 4: Global comparisons of MODIS and AERONET derived optical thickness at 470nm, encompassing 315 points from more than 30 AERONET sites (similar to those we chose) excluding coastal sites. (from [8])
6. VALIDATION OF THE JUNGE SIZE DISTRIBUTION

In the MERIS aerosol retrieval procedure or atmospheric correction phase, a Junge Size Distribution (JSD, \( n(r) \propto r^{-\nu} \)) is assumed for the aerosol scattering functions (ASF) calculations. We used here only AERONET data to investigate this assumption. Figure 9 describes the methodology we used. Basically, we compared sky radiances in the principal plane in the backscattering region simulated with a JSD and measured sky radiances at 870 nm for the three indices of refraction used in the MERIS aerosol retrieval algorithm (figure 10). The JSD is derived from the Ångström coefficient \( \alpha \) measured in close coincidence with the radiance data according to \( \nu = -\alpha - 3 \). The relative errors made on sky radiances are directly interpreted in relative errors on aerosol optical thicknesses that would be retrieved by the MERIS algorithm.

Fig. 5 : DDV spatial coverage seasonal variation (% of DDV pixels within a 100x100 pixels around the AERONET site) for (a) the equatorial forest, (b) a typical European site.

Fig. 6 : AOT at 865 nm maps derived from MODIS (a), MERIS (b) over Alta Floresta (Amazonia) on 15 July 2003, (c) is a RGB composite from L1B MERIS image

We processed this way several years of data for various AERONET sites. The main findings are summarized in Figure 11 for GSFC and Alta Floresta sites. With a 1\( \sigma \) (respectively 2\( \sigma \)) confidence interval, we can say that error induced by the choice of the JSD is 15% (respect. 30%) for GSFC when the best index of refraction is chosen. For this site the best choice is often 1.33 and sometimes 1.55. This is also confirmed by comparison of MERIS derived AOT and AERONET measured AOT at 443 nm where index 1.33 gives the best linear regression between both data sets.
Fig. 7: Cumulative histogram of the relative error on the retrieved aerosol optical thickness using a Junge power law for the aerosol size distribution. (a) GSFC (215 days analysed), (b) Alta Floresta (60 days analysed).

Fig. 8: (a) Difference between retrieved ground reflectance and DDV reflectance stored in the Look Up Tables ($\Delta p_{\text{DDV}}$) as a function of the difference between the ARVI and the ARVI threshold used for DDV detection ($\Delta \text{ARVI}$) for a 100x100 pixels zone centred on the Alta Floresta AERONET site on 2 July 2003. Ground reflectance were obtained after atmospheric correction with aerosol optical properties derived from AERONET measurements, $\tau_a(443\text{nm})=0.08$. Linear fits are performed for 3 wavelengths used in the aerosol retrieval scheme.

(b) Top: RGB composite of the sub-scene made with ground reflectance at 412, 443 and 670 nm; Bottom: Localisation of pixels for which: $\Delta \text{ARVI} > 0$ : (black, nominally classified as DDV); $\Delta \text{ARVI} > (-0.2)$ : (dark green); $\Delta \text{ARVI} > (-0.5)$ : (green).

7. VALIDATION OF THE DDV REFLECTANCE

In order to validate the DDV reflectance models and to find a way to extend the dark target approach to brighter targets we atmospherically corrected 100x100 sub-scenes using AERONET aerosol information and compared to the DDV reflectances stored in the Look Up Tables (LUTs). We kept an image subset for clear days ($\tau_a(443) < 0.15$) to minimize...
atmospheric corrections errors and residual influence of aerosol on ARVI. Indeed the surface reflectance is the critical parameter for aerosol remote sensing over land and it has to be determined as precisely as possible. MERIS has excellent radiometric performances so it is well adapted to improve surface parameters. DDV LUT’s currently used were derived from POLDER. Whereas POLDER data were very useful for the determination of Bidirectional Reflectance Distribution Functions (BRDF), MERIS should help to normalise these functions and get BRF. A typical example of surface reflectance $\rho_s$ is given in Figure 8 for Brazil. There is a linear relationship between ARVI and $\rho_s$ for DDV classified pixels ($\Delta$ARVI=ARVI-ARVIDDV $>$0) but also for non dark targets ($\Delta$ARVI as low as -0.5). This is a strong argument to introduce dynamical DDV reflectance model based on ARVI or any other spectral index. It should improve the aerosol model characterisation since red reflectance varies a lot even for DDV and it should also improve greatly the spatial coverage of the aerosol product. For that purpose it is important to introduce new LUT’s giving the slopes (in the red and the blue) of the linear relationships for each DDV model and the range $[\Delta$ARVI$_{\text{min}}$, $\Delta$ARVI$_{\text{max}}$] on which the linear correction has to be applied. This LUT shall also include a slight temporal variation as suggested by Figure 9.

![Graph showing annual variation of the slope of DDV reflectance at 670 nm](image)

Figure 9: Annual variation of the slope of DDV reflectance at 670 nm shown in Fig. 12 for the European biome.

**CONCLUSIONS AND RECOMMENDATIONS**

The core of the aerosol retrieval algorithm over land is validated since it is able to confidently detect dark target in the image and retrieve AOT in the blue with an accuracy of $0.16\tau_a \pm 0.04$. The surface pressure product is well correlated to the barometric pressure corrected from surface elevation with a standard deviation of 18hPa. This product is already useful for a consolidation of the cloud mask over land. After sensitivity studies performed with a breadboard version of the algorithm, there is still room for minor improvements of the aerosol retrieval procedure (number of aerosol models for example) and LUT’s consolidation (index of refraction climatology). But, at the present time the level 2 product which consists of the AOT at 865 nm and $\varepsilon$ is not satisfying since it suffers from an inaccurate DDV reflectance model in the red. Moreover the spatial coverage of the aerosol product is inadequate for some important parts of the globe. We thus propose to set the AOT at 443 nm as an output of the level 2 product and to extend the concept of DDV to “grey targets” with a linear dependence of the surface reflectance versus ARVI. This will allow a good spatial coverage and a better aerosol model characterisation, two important points for further use of the aerosol product for atmospheric corrections of MERIS data over land.

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