# ESTIMATION OF AEROSOL AND AIR QUALITY FIELDS WITH PM MAPPER – AN OPTICAL MULTISPECTRAL DATA PROCESSING PACKAGE

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#### **ABSTRACT:**

In the frame of the Remote Sensing applications applied to MODIS data collected by the polar orbiting satellites Terra and Aqua, operated by the NASA, we present PM MAPPER, a novel data processing system developed for air pollution monitoring. Our system has derived from the MODIS data an updated set of information consisting of AOT,  $PM_{2.5/10}$ , AQI, and surface information with increased spatial resolutions up to  $3x3 \text{ km}^2$ . With the fine spatial resolution and augmented background information, the software is effective in monitoring air pollution at local scale, especially over small urban areas with complicated topography. We carried out a validation on the data set covering Italy in a period of six months to evaluate the system's performance. The validation outcomes show that our results have good quality in comparison with MODIS standard products and a higher capacity in retrieving AOT information over land areas, especially coastlines where are nearly empty in the MODIS products. Besides, integrated surface information could be useful for further improvements of aerosol derivation.

### 1. INTRODUCTION

Since the launch in 1999 and 2002, respectively, of the two Earth Observing System's (EOS), polar orbiting satellites Terra and Aqua, operated by the National Aeronautic and Space Administration (NASA), a large amount of remote sensing data has been made available to the scientific community. These data, collected by the MODerate resolution Imaging Spectrometer (MODIS), described in detail in Salomonson et al., 1989, cover a spectral range from 0.412 µm to 14.2 µm, partitioned in 36 channels and are characterized by high spatial resolution, up to 250 m at nadir. Original MODIS data are preelaborated by a software package, the most recent version of which is known as "Collection 005" and is described in detail in Remer et al., 2004. One of the most important products of the MODIS Atmosphere algorithms applied in Collection 005 is, among other scientific information, the retrieval of the Aerosol Optical Thickness (AOT), representative of the amount of particulates present in a vertical column of the Earth's atmosphere. As reported in the above mentioned reference, these data have been used in recent years for a large amount of scientific and technological endeavours, ranging from research on climate evolution, due to aerosol impact on the characteristics of the atmosphere, to dust sedimentation in the depth of the oceans.

The use of MODIS data for air pollution monitoring, described in detail in Wang et al (2003), has recently become a promising approach because it provides global distribution of aerosol and its properties for deriving indirect estimates of particulate matter concentration, one of the major pollutants that affect air quality. The best available resolution provided by MODIS standard aerosol products, up to now, is 10x10 km<sup>2</sup> that is adequate for monitoring at global scale but not fine enough at local scale, such as urban areas. Several researchers have been aiming at deriving from the original MODIS information, presented as aerosol data integrated over 10x10 km<sup>2</sup>, more detailed information covering areas of 1.5x1.5 km<sup>2</sup> (Oo et al., 2008) or 1x1 km<sup>2</sup> (Li et al., 2005). The latter reference shows how high resolution remote sensing can be applied to densely populated urban areas, like the Hong Kong metropolitan region, to infer about pollutant distributions and air quality index. PM MAPPER developed by our research group can be set on the wake of the above mentioned works because it aims at deriving from the original data an updated set of information including Aerosol Optical Thickness (AOT), Particulate Matter concentration (PM2.5, PM10), and Air Quality Index (AQI) with increased spatial resolutions to 3x3 km<sup>2</sup>, taking advantage of new criteria for deriving from the MODIS data the spectral characteristics of land areas classified in a series of up to 40 different classes. In Section 2 of this article, we present the strategy and methodology applied to analyse the MODIS data in comparison with the standard one. Results obtained with our version of the data analysis package will be presented in Section 3, while validation of our results, in comparison with the MODIS standard products, will be discussed in Section 4. On the basis of the results obtained and of the validations made thus far, some conclusions will be drawn in section 5, together with hints about necessary future developments of the new algorithms.

## 2. METHODOLOGY

The methodology for deriving AOT information from MODIS data consists of land and ocean algorithms following the Look-Up Table (LUT) approach which matches satellite observations to simulated values in LUT to derive aerosol concentration and its properties. The algorithms have performed on land/water pixels which are cloud-free. The covered region (land/water) is determined by pixel geographical information, and clouds are

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rubbed out by cloud screening process described as MODIS cloud mask in Ackerman et al (1998).

The algorithm over ocean uses observed radiances in seven wavelengths (0.47-2.13  $\mu$ m) as input data and assumes a bimodal log-normal distribution for the size of aerosol particles which are then classified in 5 small and 6 large groups referred as "aerosol modes". In the retrieval process, for each combination of two aerosol modes with size ration  $\eta$ , the total radiance at band 0.55  $\mu$ m is calculated in order to find the best ratio  $\eta$  and the particle sizes of the small and large modes that give the best fit to the measurements in this band. The selection of aerosol model is performed until the residual error computed over 6 channels (0.55-2.13  $\mu$ m) is minimized. During this process, the optical thickness is derived in all seven channels.

The algorithm over land uses Dense Dark Vegetation (DDV) approach which derives AOT over dark pixels at the blue and red channels (0.47 and 0.66  $\mu$ m). The dark pixels, corresponding to vegetation or other land regions, are identified by using correlations between mid-IR reflectance, usually at 2.1  $\mu$ m or 3.8  $\mu$ m, and blue and red channels. However, to avoid the effects of residual cloud contamination and of some bright surfaces, 50% brightest and 20% darkest pixels are eliminated. The surface reflectances are computed from the mid-IR channel mentioned above, based on the empirical relationship between them as given in Kaufman et al., 1997. Based on the LUTs, the aerosol concentration and its properties are derived from the appropriate dynamical aerosol model (urban/industrial, biomass burning, or dust) selected by the process mentioned in detail in Kaufman and Tanré, 1997.

In an effort to improve the spatial resolution of the MODIS aerosol products from  $10x10 \text{ km}^2$  to  $3x3 \text{ km}^2$ , derive surface information and then estimate PM concentration and AQI maps for air pollution monitoring, we developed a new software package called PM MAPPER (MEEO S.r.l., 2009a). Figure 1 outlines in a schematic way the differences and correlations between the original MODIS system and the new one in which our package uses a software program called SOIL MAPPER (MEEO S.r.l., 2009b) instead of MODIS cloud mask module, modifies the aerosol algorithms over land and ocean, and estimates PM concentration and AQI maps from AOT results.

SOIL MAPPER use reflectances in eight wavelengths (0.66, 0.87, 0.47, 0.55, 1.64, 2.13, 11.03, and 12.02 µm) to identify land, water, and cloudy pixels before applying aerosol retrieval procedure. This software has been developed in the past years, based upon spectral fuzzy rule-based per-pixel classification method, originally presented and discussed in Baraldi et al., 2006. Unlike the MODIS cloud mask module, it generates a Land Cover (LC) map by using a rule based system architecture consisting of a two-level processing steps. To deal with cloud in particular, the software follows the Automatic Cloud Cover Assessment (ACCA) approach (Irish, 2000) then enhanced by spectral signature techniques for discrimination of cloud and snow covered areas (Dozier, 1989). Using the novelty of this program package, we are able to determine a set of 57 different classes, out of which 40 refer to different land types, from dense vegetation to bare soil, and the remaining classes refer to water or ice or snow covered land areas.



Figure 1. Main software modules of MODIS aerosol standard product and PM MAPPER software package.

In order to retrieve AOT concentration maps up to 3x3 km<sup>2</sup> spatial resolution, we modify both the original aerosol algorithms over land and ocean. All related procedures are considered and adapted on the smaller boxes sized 3x3 or 6x6 pixels of 1000 or 500 m MODIS measurements respectively instead of 10x10 or 20x20 pixels as presented in the original MODIS package. Processing on smaller areas leads to the requirement of adapting some thresholds, such as number of dark pixels required for a box in DDV algorithm. We solve all problems related to the definition of thresholds by the linear reduction method. Except for above modifications, the overall procedure follows the MODIS original method, as mentioned in the first part of this section.

PM&AQI retrieval is the last module added to estimate PM concentration map and then derive AQI map. PM is a complex mixture of solid and liquid particles that vary in size and composition, and can be divided into  $PM_{2.5}$  or  $PM_{10}$  by theirs aerodynamic diameters.  $PM_{2.5}$  and  $PM_{10}$  have been used to measure the air quality and can be estimated from AOT, based on the quantitative relationship between them as described in Wang et al., 2003 and Gupta et al., 2006. AQI and the related PM concentration afford useful information about the impact of air pollution on human health. This impact can be evaluated from the classification of air quality used in the US EPA and given in Table 2 (Environmental Protection Agency, 1999).

Index	Air Quality Category	PMas	PM <sub>10</sub>
maon	The Quanty Curegory	$[\mu g/m^3]$	$[\mu g/m^3]$
0-50	Good	0-15.0	0-50
51-100	Moderate	15.1-40.0	51-150
101-150	Unhealthy for sensitive groups	40.1-65.0	151-250
151-200	Unhealthy	65.1-150.0	251-350
201-300	Very unhealthy	150.1-250.0	351-420

Table 2. Air risk categories according to US EPA for  $PM_{2.5}$  and  $PM_{10}$ .

Developed by using methodologies mentioned above, PM MAPPER package has required MODIS Level 1B HDF (Hierarchical Data Format) radiance and geolocation files as input and derived an updated set of information consisting of AOT,  $PM_{2.5}$ ,  $PM_{10}$ , AQI, and surface classes at  $3x3 \text{ km}^2$  spatial resolution. The system flowchart is shown in Figure , while the system's performance and results will be presented in more detail in the next section.



Figure 3. The system overview.

## 3. RESULTS

PM MAPPER package is developed on Linux operating system using C, Fortran, and IDL programming languages. One execution tested on a computer with Intel (R) Core(TM)2 Quad CPU Q9550 @2.83 GHz, 4Gb RAM and Ubuntu 9.10 platform, takes in average about 3 minutes and requires ~ 1GB of memory. In comparison with MODIS package performance (about 5 minutes and 200MB of memory), our software requires less time but more memory for an operation. The large memory requirement is justified by the more comprehensive results and by the higher resolution but also hints at the need of future software optimization.

The software outcome consists of Aerosol Optical Thickness (AOT), Land Cover (LC), Particulate Matter concentration ( $PM_{2.5/10}$ ), and Air Quality Index (AQI) maps. Two salient characteristics of an output set are spatial resolution and land surface information.

The spatial resolution of AOT maps is increased to 3x3 km<sup>2</sup>, which provides more detailed information about the distribution of AOT. In general, coarse spatial resolution, e.g. 10x10 km<sup>2</sup> of MODIS aerosol standard products, is suitable for pollution monitoring at global scale because of providing a general view. However, smaller locations with complicated topography, such as urban areas, require observation at local scale that implies more elaborate AOT information. One illustration of our products is shown in Figure 4. It covers the areas of Italy, Bosnia, Herzegovina, Croatia, the Mediterranean sea and the Adriatic sea. Although the considered range is at nation scale, this example for local air monitoring is appropriate from the viewpoint of spatial resolution. Our result, displayed in Figure 4 (b), in comparison with MODIS aerosol product in Figure 4 (a), guarantees the consistence of general spatial distribution of AOT, especially over seas. This, in theory, proves the stableness of ocean aerosol retrieval algorithm. However, differences can be observed over land (Italy, Bosnia, Herzegovina and Croatia),

where our result presents a larger number of retrieval pixels. The coastline is another noticeable area filled by AOT values in our product and mostly empty in MODIS product (Figure 4(a)-(b)). This is due to the ineffectiveness of DDV algorithm over locations having both land and water pixels which, however, could be improved by applying processing data on smaller boxes as in our approach.

Together with the higher spatial resolution, the integrated surface information with AOT is another remarkable aspect of our results. For each pixel, corresponding to available AOT, the surface class is drawn, detailed in up to 57 values, out of which 40 are for land and 17 for other background (e.g. ice, snow, water, etc.). This integration provides another view of relationships between AOT and surfaces, which will be meaningful for investigation and correction of the factors affecting the AOT retrieval algorithm such as the correction of AOT bias on different land surfaces (Lary et al., 2009).

Starting from AOT maps, corresponding PM concentration and AQI maps are derived by our system as shown in Figure 5, which then is used directly for monitoring air pollution.



Figure 4. (a) MODIS AOT map at  $10x10 \text{ km}^2$ , (b) PM MAPPER AOT map at  $3x3 \text{ km}^2$ , and (c) classification map.



Figure 5. (a) PM concentration map and (b) AQI map derived from AOT map.

## 4. VALIDATION

In order to evaluate the PM MAPPER products, a twofold validation analysis has been performed. The first one consisted in assessing the quality of  $3x3 \text{ km}^2$  spatial outputs. The second investigated the system performance more deeply over land areas by considering its results on different land surfaces. All assessments are based on the comparison of AOT values in our products and in MODIS aerosol products. In the validation, the data set consists of 15 images selected out of a total of 180 images covering Italy in a period of 6 months, from January 2008 to June 2008.

In the first validation, we evaluate the products at  $3x3 \text{ km}^2$  in comparison with MODIS products at  $10x10 \text{ km}^2$  over land, ocean, and both areas. Two parameters, correlation coefficient and the number of retrieved pixels, are considered. To avoid problems due to the different resolutions, all AOT maps are resampled at  $1x1 \text{ km}^2$  resolution before any comparison. The results show the high correlation coefficients of our AOT with respect to MODIS AOT as plotted in Figure 6. The integrated AOT, a combination of aerosol over both land and ocean, has the correlation coefficient 0.88 in average with a deviation from 0.78 to 0.95. In more particular, the scattering plots of correlation coefficients between PM MAPPER AOT and corresponding MODIS AOT in the best and the worst cases are shown in Figure 7(a)-(b) respectively.

The number of retrieval pixels is representative for the map covering capacity. Figure 8(a) shows that the largest number of retrieved pixels is achieved by our software rather than by the original MODIS version (about 43.10% more pixels in average). This result is due to a large increase over land in spite of a small decrease over ocean (Figure 8 (b)-(c)). This

improvement comes from our approach in which we applied AOT retrieval algorithm on smaller boxes and used SOIL MAPPER instead of MODIS cloud mask module to identify land, water, and cloudy pixels.



Figure 6. Correlation Coefficient of PM MAPPER with respect to MODIS version



Figure 7. The scattering plot of (a) the best and (b) the worst correlation coefficient case, 0.95 and 0.78 respectively.





Figure 8. Number of retrieved AOT pixels on (a) Land and Ocean, (b) only Land, and (c) only Ocean.

Images

4 5 6 7 8 9

(c)

10 11 12 13 14 15

The second validation is carried out to consider more deeply results at  $3x3 \text{ km}^2$  on a stratified basis using integrated surface information detailed in up to 40 land classes (see Table 9). The purpose of the stratified analysis is to verify where the applicability of DDV algorithm is appropriate, that is, to investigate the relationship between the MODIS AOT values and PM MAPPER AOT values for different land cover classes.

For each land class, we calculated its darkness as the ratio of the number of dark pixels to the total number of pixels. One pixel is considered as a dark pixel when given conditions on the band 2.1  $\mu$ m in DDV algorithm are satisfied. The darkness will decide the quality of aerosol optical thickness derivation over the class because aerosol derivation is affected by the uncertainty in the scattering phase function, as explained in Remer et al., 2004. The number of retrieved AOT pixels and the AOT correlation coefficient with respect to MODIS product are only computed over pixels having integrated information which is AOT and corresponding land label.

The validation results are divided into 4 groups as presented on Table 9. The first and second groups represent land classes having poor statistics on dataset and low correlation coefficients. In this case, more data need to be investigated. Group 3 includes two large and bright classes (16.3% and 46.1% of dark pixels for Bright Barren Land 2 and Bright Barren Land 4, respectively) where, in theory, the DDV retrieval algorithm is expected to be ineffective. However, the data analysis shows bad results only over Bright Barren Land 2 (correlation coefficient 0.627), whereas good results are obtained over Bright Barren Land 4 (correlation coefficient 0.809). The accuracy of dark pixel scanning over these classes can be considered as a reason for the noted differences. Even if this scanning performs well, over a very bright surface such as Bright Barren Land 2, the new improvements of aerosol derivation should be investigated. Group 4 consists of the residual classes that are dark and are characterized by a large number of retrieved pixels. Most of them have good correlation coefficients, but some can be candidates for improvements (i.e., Average Herbaceous Rangeland or Average Barren Land 2).

Labels	D.	N.	C.	G.
Bright Weak Vegetation	0	0	0.000	1
Bright Strong Shrub	0	0	0.000	1
Rangeland	0	0	0.000	1
Dark Strong Shrub		Ű	0.000	-
Rangeland	0	0	0.000	1
Strong Herbaceous			0.000	-
Rangeland	0	0	0.000	1
Dark Barren Land 2	0	0	0.000	1
Bright Barren Land 1	0.989	409	0.387	2
Average Barren Land 1	1	1,450	0.539	2
Dark Barren Land 1	1	102	0.557	2
Strong Barren Land 2	0.982	2,775	0.674	2
Dark Barren Land 4	1	191	0.708	2
Dark Peat Bogs	1	99	0.709	2
Strong Barren Land 1	1	485	0.736	2
Bright Strong Vegetation	1	76	0.755	2
Dark Weak Vegetation	0.989	110	0.835	2
Bright Barren Land 2	0.163	105,765	0.627	3
Bright Barren Land 4	0.431	345,917	0.809	3
Average Herbaceous		· · · · ·		
Rangeland	1	17,985	0.746	4
Average Barren Land 2	0.999	6,436	0.747	4
Dark Range Land	1	83,288	0.764	4
Dark Strong Vegetation	1	87,393	0.765	4
Bright Peat Bogs	0.998	3,806	0.782	4
Wet land	0.996	13,829	0.786	4
Shadow Barren Land	0.978	8,914	0.799	4
Dark Average Shrub				
Rangeland	1	50,557	0.809	4
Strong Barren Land 3	1	52,505	0.814	4
Shadow Vegetation	0.921	76,124	0.816	4
Bright Average Shrub				
Rangeland	0.999	697,678	0.816	4
Strong Barren Land 4	0.999	190,492	0.817	4
Dark Barren Land 3	1	129,072	0.828	4
Strong Barren Land 5	0.997	48,374	0.831	4
Bright Barren Land 3	0.908	41,569	0.833	4
Very Bright Average				
Vegetation 2	0.998	976,442	0.838	4
Average Barren Land 4	1	206,557	0.839	4
Mid tone Peat Bogs	1	5,225	0.841	4
		1,133,1		
Bright Average Vegetation	1	62	0.855	4
Very Bright Average				
Vegetation 1	1	392,399	0.856	4
Bright Rangeland	0.999	231,669	0.856	4
Dark Average Vegetation	0.999	308,450	0.863	4
Mid tone Rangeland	1	386,860	0.878	4
Average Barren Land 3	1	326.197	-0.880	4

Table 9. The performance of PM MAPPER at 3x3 km<sup>2</sup> over difference land classes (D: Darkness, N: Number of retrieval AOT pixels, C: Correlation Coefficient, G: Group)

In conclusion, the first validation results show that PM MAPPER products have good quality in comparison with MODIS standard aerosol products and higher capacity in retrieving AOT information (larger number of retrieved pixels). The second validation reinforces the previous result with the high correlation coefficient over most of dense surface classes. This validation also groups and points out some potential land

classes where the aerosol retrieval algorithm needs to be improved.

## 5. CONCLUSION AND FUTURE WORKS

In this article, we presented the PM MAPPER, a multispectral data processing package for aerosol and air quality field estimation. The software has derived from MODIS data a set of information consisting of AOT,  $PM_{2.5}$ ,  $PM_{10}$ , AOT, and surface classes with increased spatial resolutions up to  $3x3 \text{ km}^2$ . PM MAPPER products are characterized by fine spatial resolution and integrated background information, provided by the SOIL MAPPER, in which a classification system derives automatically, from MODIS data, cloud and land cover details classified in up to 57 classes.

With the fine spatial resolution, our products are suitable for global- to local-scale air monitoring applications. The 10x10 km<sup>2</sup> resolution of the MODIS standard aerosol product has been increased to 3x3 km<sup>2</sup>, providing more details of the emissions sources as well as of the AOT distribution map. Furthermore, the higher spatial resolution and the usage of the classification system have increased the total number of retrieved pixels in the whole scene, especially over land areas and along coastlines.

Moreover, integrated surface information is useful in analysis and improvements of DDV algorithm that uses dark pixels to derive AOT information over land. As shown in the second validation results, the DDV algorithm has performed well on most of dark classes but this approach has limitations on some bright and special dark areas in which improvement is necessary.

In future, we will continue to carry out the validation that compares the results derived by satellite-based and by AErosol RObotic NETwork (AERONET) ground-based measurements in order to verify the consistency of satellite-based AOT products. Besides, we will be aiming at increasing the spatial resolution up to  $1x1 \text{ km}^2$  and improving the aerosol retrieval algorithm over bright and dark surfaces.

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