SATELLITE CHARACTERIZATION OF POWER PLANT AEROSOL EMISSIONS

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ABSTRACT

Aerosol optical thickness is a major atmospheric quantity tuning the Earth radiation budget therefore it has to be determined on a global scale, both over land and ocean. Since the sources of most aerosols (mainly of anthropogenic origin) are located over land, the satellite remote sensing of aerosols over land is particularly important to quantify and characterize these particles in the atmosphere.

The aim of the present work is the identification and characterization of aerosols plumes emitted from the Portuguese Electrical Company (EDP) Power Plants using satellite measurements, with the purpose of monitoring the emissions of pollutants and of studying their atmospheric dispersion. The methodology is based on calculations of radiative transfer in the atmosphere that, properly combined with satellite measurements, allow for the detection and determination of the actual amount of aerosols in the atmosphere and some of their physical characteristics. The columnar amount of pollutants obtained in this way (aerosol optical thickness) is compared with the emissions of particles that are monitored on the top of the power plant towers, in order to validate the values retrieved from the satellite-based method.

Satellite measurements from the MODerate Resolution Imaging Spectroradiometer (MODIS) were used in the study, since they present the adequate spectral channels and spatial resolution (250 x 250 m^2 in some spectral channels) to observe and monitor disturbances in the Earth-atmosphere system. At the same time, information about the wind direction and intensity at the power plant towers altitude, and the aerosol back-trajectories analysis of 24 hours, at the same height, were used in order to guarantee that there is no contamination from other aerosol sources apart from the one under study.

The analysis of the aerosol optical thickness values obtained with the satellite based methodology, confirmed that a higher value of optical thickness exists in the areas where the Power Plants are located and, in some of them, a good agreement can be observed (high positive correlation) between the values of the optical thickness obtained from the satellite data and the aerosol emissions measured at the top of the power plant towers.

1. INTRODUCTION

Among the several agents that can affect climate, aerosols play a very important role (IPCC 2001). These small particles that are in suspension in the atmosphere, have the capacity to scatter and to absorb the solar radiation (aerosol direct effect) (Costa et al. 2004b) and also to interact with clouds modifying their physical properties and their residence time in the atmosphere (aerosol indirect effect) (Breón et al. 2002; Rosenfeld 1999; Costa 2004). The aerosols that strongly scatter the radiation can provoke an increase of the planetary albedo and consequently a surface cooling. The aerosols that absorb radiation may provoke an atmospheric heating. The aerosol residence time in the atmosphere (troposphere) is very variable. It depends on the particle dimension the largest and heavier aerosols tend to fall faster whereas the smallest and lighter can be transported in the atmosphere, staying there during days or weeks (Ramanathan et al. 2001). Desert dust originated from sand storms, anthropogenic emissions originated from industrial activity, marine salts and biomass burn are very important sources of atmospheric aerosols (King et al. 1992). For example, the desert dust coming from the Sahara Desert is often transported across northern Africa to the Atlantic Ocean, reaching Portugal (King et al. 1992; Silva et al. 2003).

In the last few years a strong concern exists related to the impact that the human activity may have in the atmosphere and in climate change (IPCC 2001). The aim of the present work is the characterization and identification of aerosol plumes emitted from power plants of the Portuguese Electrical Company (EDP) (located in the areas of the Carregado, Barreiro, Setúbal and Sines, in Continental Portugal), using satellite and ground-based measurements (CIMEL spectrophotometer). The main objectives are:

- The identification of aerosols plumes emitted from the electricity company (EDP), using satellite measurements;
- The determination of the plume's extension and particle's columnar amount present in the atmosphere.
- The determination of the aerosol particles physical characteristics as well as the aerosols nature in the atmospheric column.

The methodology is based on radiative transfer calculations in the atmosphere that properly combined with satellite radiance measurements and with surface measurements of the spectral solar extinction, allow for the detection and determination of the aerosol amount in the atmosphere and of some of their physical characteristics. After determining the aerosol amount in the atmospheric column (aerosol optical thickness), this value is properly corrected through the removal of the 'background pollution' (aerosol amount present in the atmospheric column that is not originated from the power plant). The columnar amount of pollutant obtained like this, is then compared with the particle emissions monitored at the exit of the power plant tower, in order to validate the results obtained from the satellite based method.

In the last years, new generation instruments have been developed and installed in satellites, allowing for accomplishing more detailed measurements, with better space and spectral resolution. The aerosol remote sensing using sensors on board satellites allows for monitoring the sources, the transport and the places of deposition of these particles (Tanré et al. 1997; Kaufman et al. 1997; King et al. 1992; Costa et al. 2004a; Santos et al. 2004). Measurements from the MODerate Resolution Imaging Spectroradiometer (MODIS) were used (Barnes et al. 1998). This spectroradiometer offers good spectral and spatial characteristics to observe and monitor disturbances in the Earth-Atmosphere system and for studies of atmospheric dispersion of pollutants.

The next section briefly describes the methodology. The results obtained along with their discussion are presented in section 3 followed by the final considerations in section 4.

2. METHODOLOGY

In order to study several situations for each of the power plants, several days along the year of 2003 were selected. To minimize the uncertainty associated with the aerosol quantity satellite retrieval, the selection of the days was done considering only clear sky images, as well as the favourable wind conditions in order to avoid the emission of particles from other companies located in the neighbourhood of the EDP Power Plants under study. Also the three-dimensional back trajectories were calculated as an additional tool, in order to trace the origin of the air masses under study, taking as starting point the geographical coordinates and height of the power plant towers. The trajectories were calculated using the NOAA HYbrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT4) (Rolph 2003), over a duration of 12, 24 and 72 hours and using the meteorological input fields from the 6-hourly FNL archive data generated by the National Center for Environmental Prediction Global Data Assimilation System (NCEP GDAS).

The main aerosol quantity retrieved here is the aerosol optical thickness (AOT), related with the concentration of this type of particles in the atmosphere. The aerosol optical thickness values are obtained through the method developed and described below, based on the combination of satellite measurements with radiative transfer calculations in the atmosphere, as illustrates in Figure 1.

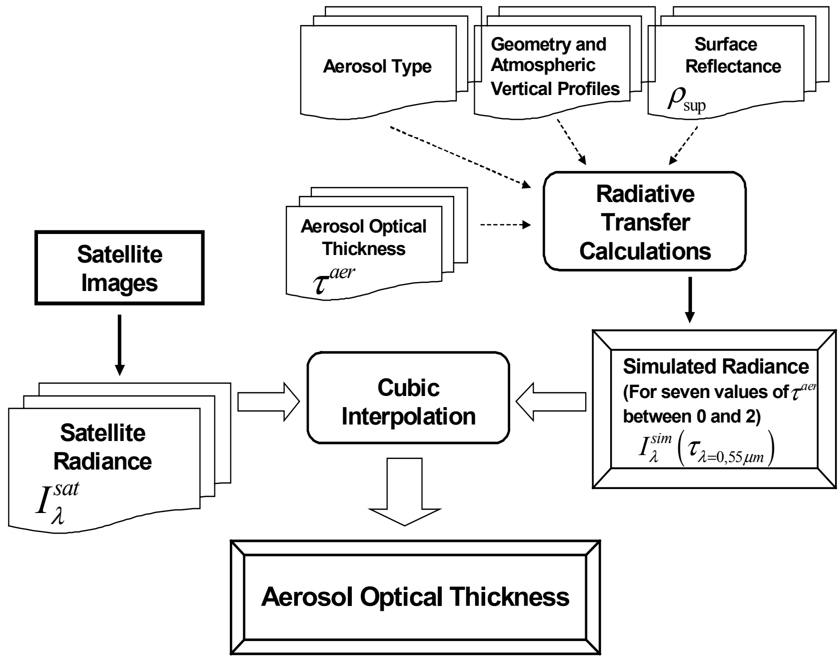

Figure 1 – Scheme of the methodology.

MODIS measurements, on board Terra and Aqua satellite, are characterized by a good spectral and space resolution, in the spectral regions of the visible, near infrared and thermal infrared. The measurements are made in a wide spectral range (between 0.4μm to the 14.4μm), in 36 spectral bands. The space resolution varies between 1km, 500m or 250m, depending on the spectral band. The present methodology uses channels 1 (620-670 nm) and 2 (841-876 nm) to retrieve the aerosol optical thickness

The AOT is retrieved making use of the MODIS measured radiances, as well as of the radiative transfer code (RSTAR5B), developed by Nakajima and Tanaka (1988). This code simulates the radiation fields in the Atmosphere – Earth – Ocean system for the spectral range between 0.3μm and 200μm.

In order to simulate the radiance values, the radiative transfer code was used varying:
- the aerosol type (marine salt, desert dust, industrial pollution, forest fire and rural);
- the surface reflectance values (0.05, 0.1, 0.2, 0.3, 0.4 and 0.5);
- the sun and satellite geometry (solar zenith angle, satellite zenith angle and relative azimuth angle);
- the aerosol optical thickness (0.01, 0.1, 0.2, 0.5, 1.0, 1.5 and 2).

The simulated radiance at the top of the atmosphere is then compared with the satellite measured radiance, in order to extract information about the aerosol amount present in the atmospheric column (AOT).

The surface reflectance is a very important parameter for the atmospheric properties remote sensing. In the continents, the largest component of the solar radiation reflected, in conditions of clear sky, is owed to the surface reflection. Consequently, the determination of the atmospheric composition through the reflected radiation requests an accurate knowledge of the surface reflection contribution. The surface reflectance is determined here with the method presented by von Hoyningen-Huene et. al (2003):

$$\rho_{surf}(\lambda) = C_{veg} \cdot \rho_{veg}(\lambda) + (1 - C_{veg}) \cdot \rho_{soil}(\lambda) \quad (1)$$

where $\rho_{veg}(\lambda)$ is the surface reflectance when it is covered by vegetation and $\rho_{soil}(\lambda)$ is the surface reflectance when it doesn't have vegetation but is covered only by soil (sands, bare soil, etc). $C_{veg} = NDVI$ allow for estimating the fraction covered by vegetation that is calculated through equation 2:

$$NDVI = \frac{\rho(\lambda_8) - \rho(\lambda_6)}{\rho(\lambda_8) + \rho(\lambda_6)} \quad (2)$$

where $\rho(\lambda_6)$ and $\rho(\lambda_8)$ are the MODIS reflectances in channels 1 (620-670 nm) and 2 (841-876 nm), respectively.

The radiance measured by the satellite incorporates not only the surface contribution, but also the radiance originating from the atmosphere that depends on the aerosol type and on the aerosol optical thickness present in the atmosphere, on the sun and satellite geometry (zenital and azimutal angles), and on the atmospheric vertical profile (midlatitude Summer or Winter, depending on the selected day). The radiance at the top of the atmosphere is then simulated with the radiative transfer code, and then adjusted to the satellite measured radiance, applying a cubic interpolation, obtaining as a result the value of the aerosol optical thickness corresponding to the best adjustment between the simulated spectral radiance and the satellite measured radiance. The aerosol optical thickness values obtained in this way are then related with the particle emissions values monitored at the top of the power plant towers under study.

To obtain the effective aerosol optical thickness corresponding to the real emissions of the EDP Power Plants, it was necessary to remove the contributions external to the stations under study, originating from the surrounding area of the Power Plants or from more distant areas. To do so, the wind direction was taken into account, obtaining the aerosol optical thickness in the opposite area with respect to the plume direction when emitted at the chimneys. For each of the Power Plants under study, the mean background aerosol optical thickness value was then calculated.

3. RESULTS

Table 1 presents the days and time of the satellite images selected for the study, as well as the aerosol type selected accordingly to the geographical origin of the air masses, obtained from the analysis of the back trajectories.

Satellite and Instrument	Date	Time (UTC)	Aerosol Type	Particle Source
Terra MODIS	14/01/03	10:55	Rural	Iberian Peninsula (East)
	05/04/03	11:35	Rural	Iberian Peninsula (East)
	07/0/034	11:25	Rural	Iberian Peninsula (East)
	11/05/03	11:10	Sea Salt	Atlantic Ocean (South)
	12/05/03	11:55	Rural	Iberian Peninsula (East)
	20/06/03	12:00	Desert Dust	Northern Africa
	21/06/03	11:05	Rural	Iberian Peninsula (East)
	07/08/03	12:00	Sea Salt	Iberian Peninsula (South)
	11/08/03	11:35	Sea Salt	Iberian Peninsula (South)
	04/10/03	11:00	Sea Salt	Iberian Peninsula (South)
	05/10/03	11:40	Sea Salt	Iberian Peninsula (South)
	19/11/03	11:10	Sea Salt	Atlantic Ocean (South)

Table 1 – Day and time of the satellite images selected for the study and aerosol type considered.

The area under study was divided in two, one that includes Great Lisbon area and that contains three of the four Power Plants considered (Carregado, Barreiro and Setúbal) and an area that includes the Sines Power Plant. This second area is of great interest, once it is possible, choosing the appropriate wind direction, to visualize the contaminated area directly related to the plume coming from the chimney. The first area, where the first three are located, is more complex since it is usually highly contaminated with the background pollution originating from the Great Lisbon area.

The effective aerosol optical thickness values were calculated from the satellite images with three spatial resolutions: 1km, 500m and 250m. The mean values of the aerosol optical thickness presented in Table II correspond to the satellite images with the resolution of 250m. Both standard deviation and the relative standard deviation of the effective aerosol optical thickness are also presented in Table II.

CARREGADO				
DATE	**TOTAL MASS PARTICLE (KG)**	**EFFECTIVE AOT MEAN VALUE**	**STANDARD DEVIATION**	**RELATIVE STANDARD DEVIATION (%)**
20/06/03	28	0.35	0.23	66
07/08/03	67.2	0.38	0.12	32
11/08/03	61.2	0.37	0.18	26
BARREIRO				
DATE	**TOTAL MASS PARTICLE (KG)**	**EFFECTIVE AOT MEAN VALUE**	**STANDARD DEVIATION**	**RELATIVE STANDARD DEVIATION (%)**
07/04/03	34	0.51	0.3	59
11/05/03	22.3	0.33	0.26	79
12/05/03	72.3	0.62	0.38	61
04/10/03	46.9	0.56	0.21	38
05/10/03	45.8	0.51	0.16	31
SETÚBAL				
DATE	**TOTAL MASS PARTICLE (KG)**	**EFFECTIVE AOT MEAN VALUE**	**STANDARD DEVIATION**	**RELATIVE STANDARD DEVIATION (%)**
20/06/03	90	0.45	0.18	40
21/06/03	118	0.5	0.26	52
07/08/03	39	0.24	0.08	33
11/08/03	27.7	0.37	0.16	43
SINES				
DATE	**TOTAL MASS PARTICLE (KG)**	**EFFECTIVE AOT MEAN VALUE**	**STANDARD DEVIATION**	**RELATIVE STANDARD DEVIATION (%)**
14/01/03	67.8	0.16	0.13	81
05/04/03	242.4	0.21	0.17	81
20/06/03	538	0.43	0.31	72
21/06/03	465	0.32	0.17	53
07/08/03	139.5	0.17	0.07	41
11/08/03	290.7	0.27	0.25	93
19/11/03	450.7	0.28	0.12	43

Table 2 – Comparison between the mean aerosol optical thickness values and the total mass particle emitted in the same period, for each of the Power Plants, after correcting for the background aerosol optical thickness.

The graphs of the following figures illustrate for each of the selected Power Plants, the relationship between the effective aerosol optical thickness obtained from the satellite images and the emissions of particles measured at the top of the power plant towers. The vertical bars are the standard deviations already presented in Table II

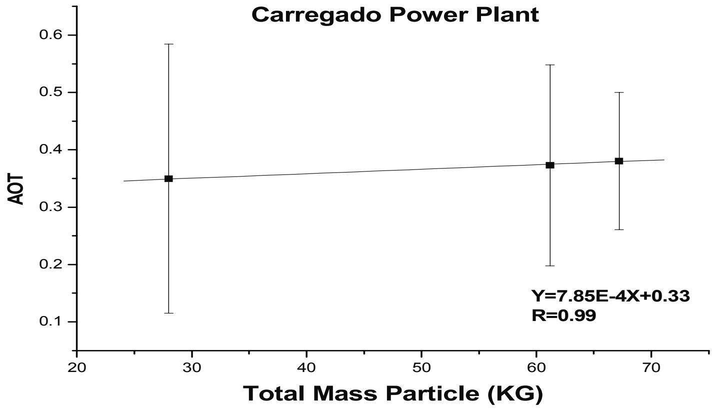

Figure 2 – Relationship between the emission of particles and the mean aerosol optical thickness value of the obtained from the satellite images for the Carregado Power Plant.

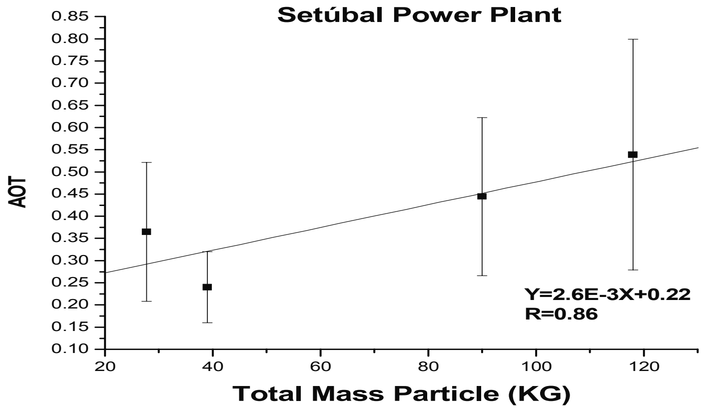

Figure 3 – Relationship between the emission of particles and the mean aerosol optical thickness value of the obtained from the satellite images for the Setúbal Power Plant.

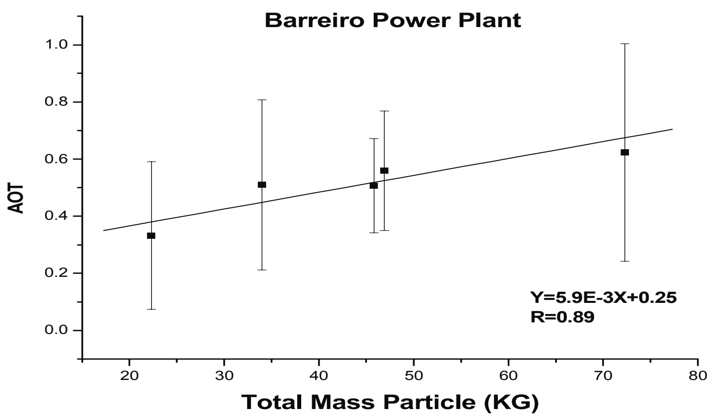

Figure 4 – Relationship between the emission of particles and the mean aerosol optical thickness value of the obtained from the satellite images for the Barreiro Power Plant.

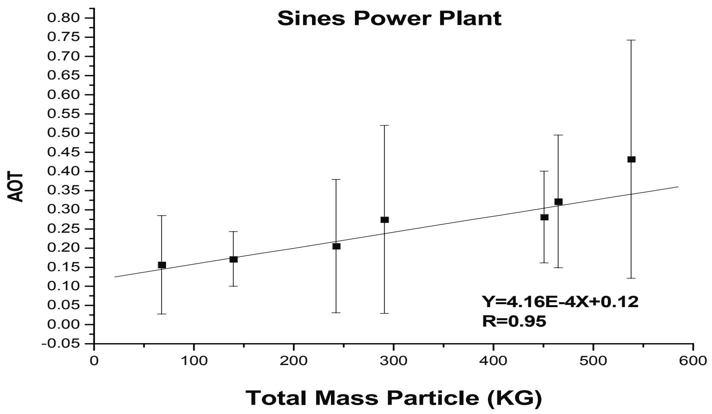

Figure 5 – Relationship between the emission of particles and the mean aerosol optical thickness value of the obtained from the satellite images for the Sines Power Plant.

The graphs in the previous figures show that the variation of the aerosol optical thickness is directly proportional to the particle emissions measured at the top of the chimneys, that is, larger values of the emissions correspond larger values of the satellite derived aerosol optical thickness (Santos 2005). The great standard deviations reveal the high spatial variability of the satellite images from which the aerosol optical thickness of the aerosol plumes were retrieved.

4. FINAL CONSIDERATIONS

From inspection of the aerosol optical thickness maps obtained from the developed satellite based methodology, can be concluded that higher values of the aerosol optical thickness exist in the areas where the Power Plants are located. A good agreement between the values of the aerosol optical thickness obtained from the satellite data and the aerosol particles emissions measured at the top of the power plant towers could be observed. For these results, the following factors have significantly contributed: knowledge of the wind speed (intensity and direction) at the power plant tower height; determination of the background aerosol optical thickness that was used to remove to the value obtained directly from the satellite images the background contamination. The methodology revealed therefore to be appropriated for the identification and quantification of the analyzed Power Plant aerosol emissions.

However, it will be necessary to make a deeper study, particularly for the Lisbon area, highly contaminated with the background pollution that most of the times difficult the identification of the power plant aerosol plumes from the satellite images. To do so, it will be necessary to refine the present methodology combining it, if possible, with surface measurements, which are essential to reduce the uncertainty associated with the determination of the aerosol optical thickness.

5. ACKNOWLEDGEMENTS

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