DETECTING AIR POLLUTION FROM SPACE USING IMAGE-BASED METHOD

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ABSTRACT

Satellite sensors have provided new datasets for monitoring regional and urban air quality. Satellite sensors provide comprehensive geospatial information on air quality with both qualitative remotely sensed imagery and quantitative data, such as *aerosol optical depth.* This paper presents a new method for retrieving aerosol optical thickness. The method is based on the determination of the aerosol optical thickness through the radiative transfer calculations and the 'tracking' of the suitable darkest pixel in the scene. The proposed method that needs no a-priori information has been applied to Landsat- TM & ETM+, Spot-5 and IKONOS data of three different geographical areas: West London, and Cyprus. The retrieved aerosol optical thickness values show high correlations with in-situ visibility data acquired during the satellite overpass.

1. INTRODUCTION

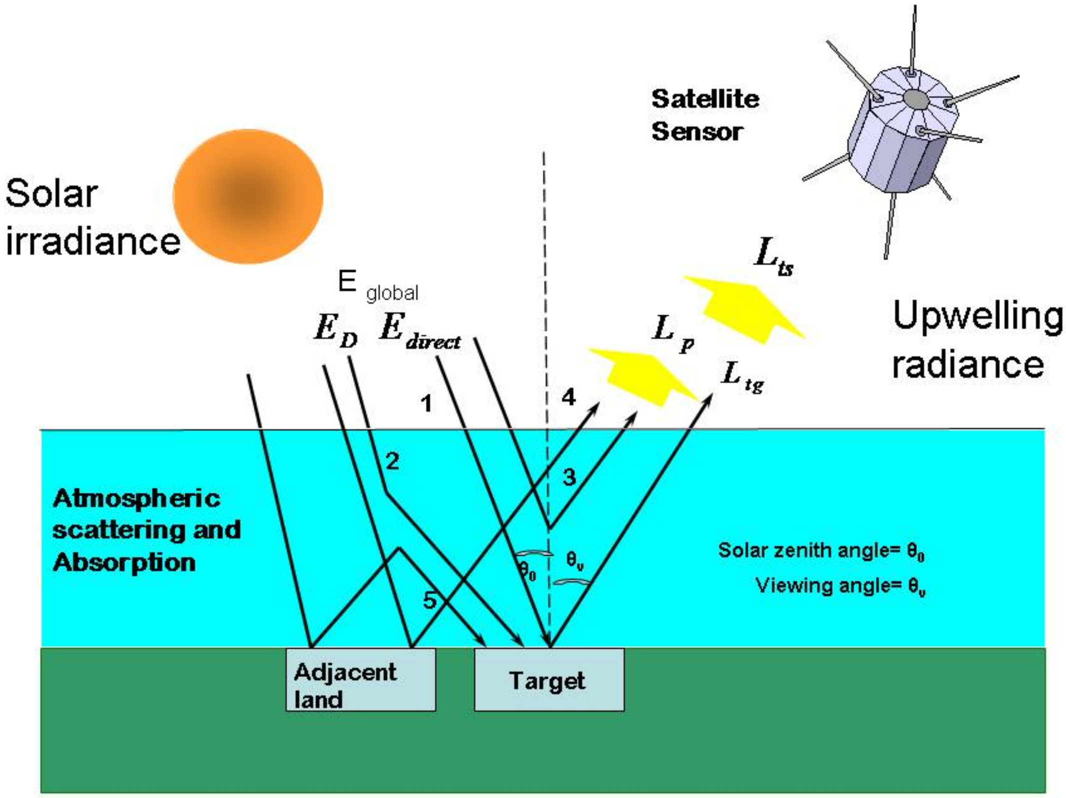
Atmospheric pollution is one of the major issues that received considerable attention by local and global communities. Air quality monitoring stations have been established in major cities and provide means for alert. The measuring stations are scarcely distributed and they do not provide sufficient tools for mapping atmospheric pollution since air quality is highly variable [7, 9 and 19]. However, satellite remote sensing is certainly a valuable tool for assessing and mapping air pollution due to their major benefit of providing complete and synoptic views of large areas in one image on a systematic basis due to the good temporal resolution of various satellite sensors.

The use of satellite remote sensing to assess and map atmospheric pollution has received extensive attention from researchers who developed a variety of techniques [9, 12, 15 and 19]. The key parameter for assessing atmospheric pollution in photochemical air pollution studies is the aerosol optical thickness [9], which is also the most important unknown of every atmospheric correction algorithm for solving the radiative transfer (RT) equation and removing atmospheric effects from satellite remotely, sensed images. The aerosol optical thickness has been used as a tool of assessing atmospheric pollution [7, 9 and 12]. Indeed, this paper presents a new fully-image based method for determining the aerosol optical thickness through the radiative transfer calculations and the 'tracking' of the suitable darkest pixel in the satellite images.

2. BASICS: ATMOSPHERIC CORRECTION

The atmospheric contribution to the satellite signal occurs when the electromagnetic radiation from the sun passes through the atmosphere, is reflected by the earth and then again passes through the atmosphere and is detected by the satellite sensor as shown in Figure 1. The interaction processes which occur during the two-way passage through the atmosphere are mainly scattering and absorption processes. These processes add to or decrease the true ground-leaving radiance and their intensity is dependent on the wavelength. The basis of any correction of a satellite image is to identify and understand the process which contaminates the image. In the case of atmospheric effects, the origin for any attempt to perform atmospheric correction to satellite data is the setting up of an equation [2] which describes all the processes with the various atmospheric parameters and variables, that contributes to the attenuation of the signal received by a satellite sensor (see Figure 1). This equation is called the radiative transfer (RT) equation.

Bearing in mind that the atmospheric effects are mainly caused by scattering and absorption of atmospheric gases, aerosol and clouds, the most important point in order to perform an atmospheric correction is to be aware of the optical characteristics of the atmosphere: mainly the aerosol optical thickness and secondly the single scattering albedo and the gaseous absorption. The main problem in atmospheric correction is the difficulty in determining these optical characteristics.



1. Direct solar irradiance; **2.** Diffuse sky irradiance; **3.** Atmospheric radiation
4. Scattering from surrounding land; **5.** multiple surface-atmosphere reflections.

E_D	is the diffused sky irradiance corrected for earth-sun distance variation.
E_{direct}	is the direct solar irradiance
L_p	is the atmospheric path radiance
L_{ts}	is the target radiance at the sensor,
L_{tg}	is the target radiance at the ground level transmitted from the target of interest toward the sensor,
θ_v	is the satellite viewing angle
θ_0	is the solar zenith angle

Figure 1. Diagram showing various paths of radiance received by the satellite remote sensing sensor.

3. LITERATURE REVIEW: METHODS FOR DETERMINING THE AEROSOL OPTICAL THICKNESS

Atmospheric aerosol is an important parameter both in any atmospheric correction method for satellite remote sensing and in climate changing and air pollution studies. It is also one of the most uncertain parameters for such studies. The determination of the optical properties of aerosol particles is the most difficult part of any atmospheric correction method that is applied to determine the true reflectance values from the satellite remotely sensed imagery. The key factor that contributes significantly to the at-satellite signal is the *atmospheric aerosols*. Atmospheric effect in the visible band is affected by the aerosol.

Since the optical properties of aerosols are rather difficult to estimate, many methods for determining such parameters have been discussed by several investigators either as a separate procedure or as a part of atmospheric correction methods [7, 9 and 10]. The methods for determining the aerosol optical properties such as the aerosol optical thickness include ground measurements using Sun-photometers and several methods applied on satellite imagery such as the following:

- `the ocean method' applied over clear water using visible data or infrared data (for example, Griggs 1975 [4]);
- the `brightness method' applied above land using data in the visible spectrum [3];
- the `contrast-reduction method' applicable over land [17] or a mixture of land and water [12];
- the `dark vegetation method' using long-wavelength visible data [12];
- the 'temperature attenuation' procedure [14],
- The 'differential textural analysis method' [11 and 15].

4. METHODOLOGY

The method described below is the 'modified version' of the one presented by Hadjimitsis *et al.* (2003) [6].

1. Select a sub-image from the desired scene
2. Check the image contrast (C) for the selected sub-image:

$$C\ \%= [DN_{dark\ target}-DN_{neighbourhood}] / [DN_{neighbourhood}] .100$$

3. Choose the suitable dark-target in the scene and masked out the land around the selected dark target based on the following criteria:
    a) Thorough examination of the statistics for each image (frequency, count threshold): A pixel count threshold of: >15 and > 10 for sub-scenes of 800 x 800 and 600 x600 (rows x columns) is set out either the dark target is not selected
    b) Inspection of histograms (e.g. shape)
    c) Type of dark object and its spectral signature/reflectance: eutrophic water body: 0 -5 % in the blue bandwidth for Landsat, SPOT and IKONOS sensors.
    d) Examine possible noise and data recording

4. Input parameters:
    a) Ozone transmittance (t_{O3}) =1,
    b) Water vapour transmittance (t_{H20}) =1,
    c) Aerosol single scattering albedo=1 (perfectly scattering aerosol);
    d) Surface reflectance of the dark-target: ranges from 0 %-5 % for eutrophic water bodies and 7-10 % for asphalt targets [7].
5. The algorithm determines the Rayleigh optical thickness and Rayleigh scattering phase function from the equations provided by Forster (1984).
6. Use values from steps (4) t_{O3} =1, t_{H20} =1, Aerosol single scattering albedo=1, and surface reflectance=0 % and run the darkest-pixel atmospheric correction using radiative transfer calculations [6]. Determine the *aerosol optical thickness* from the formulae given by Hadjimitsis and Clayton (2004) [5].
7. Use the value of the aerosol optical thickness from step 6 and correct the satellite image. Check the new image contrast after atmospheric correction and comparing it with the result found from step (2). At this step 7, atmospheric effects must be ideally removed. This means that the aerosol optical thickness after the perfect correction must be zero: $\tau_a=0$. Try different reflectance values from step 4 (d) until the highest contrast value is obtained i.e. *Clear conditions.* The one corresponds to the corrected image with the maximum contrast value. The idea is that a sharp contrast (i.e. high contrast values) is obtained when the

atmospheric effect is minimized and for the very hazy atmospheres contrast value is reduced (i.e. low contrast values).

8. *Mark the surface reflectance value from step 7 and r*epeat step (5) with the same values except the surface reflectance value (use the one found from step 7). The result is the final value of the aerosol optical thickness for the selected area of interest.

5. APPLICATION

5.1 West London Area (UK): Heathrow Airport

The proposed approach was applied to Landsat-5 TM band 1 (0.45-0.52 μm) images of the London Heathrow area (see Figure 2) acquired on 17th of May, 2nd of June 1985, 4th of July 1985, 28th of September 1985 and 28th of June 1986.

Figure 2. Partial scene: Landsat-5 TM image of Heathrow Airport area (UK) acquired on 2nd of June 1985.

There is evidence that the visibility is related with the aerosol optical thickness as shown from Forster (1984) and Tanre *et al*. (1979). Therefore, the available visibility values (see Table 1) recorded at the Heathrow Meteorological station during the satellite overpass provides can be used to assess the proposed method for the determining the aerosol optical thickness. By relating the determined aerosol optical thickness with the visibility values shown in Table 1, a logarithmic regression was fitted with a correlation coefficient r^2=0.82. The observed significance for the regression model was 0.02<0.05.

TABLE 1. Calculated aerosol optical thickness for the three Landsat-5 TM band 1 images of Heathrow Airport area

Image Date	Determined Aerosol Optical Thickness	Visibility (km)	RH %
2-June-1985	**0.13**	**26.2**	55
17-May-1985	0.58	13.2	54.1
28-September-1985	0.60	6.9	68.4
28-June-1986	0.70	5.4	51.6
4-July-1985	0.76	7.5	60.4

The authors reproduced the plots obtained from Forster (1984) and Tanre *et al*. (1979 & 1990) [16 and 17] and those data have been plotted on the same Figure 3 so as to compare their results. The author's results show an agreement with Forster's *aerosol optical thickness Vs visibility results* and a small deviation from Tanre's model. From Table 1, it is apparent that for the image acquired on 4/7/85, the aerosol optical thickness was significantly increased. This means that aerosol concentrations might be increased on 4/7/85 due to high emissions from primary sources, such as road transport and industrial activities, which are the main sources of aerosol temporal variability [1]. Therefore the air pollution in the Heathrow area was more significant in July and May and less significant on June. The visibility data found at the satellite overpasses support this finding.

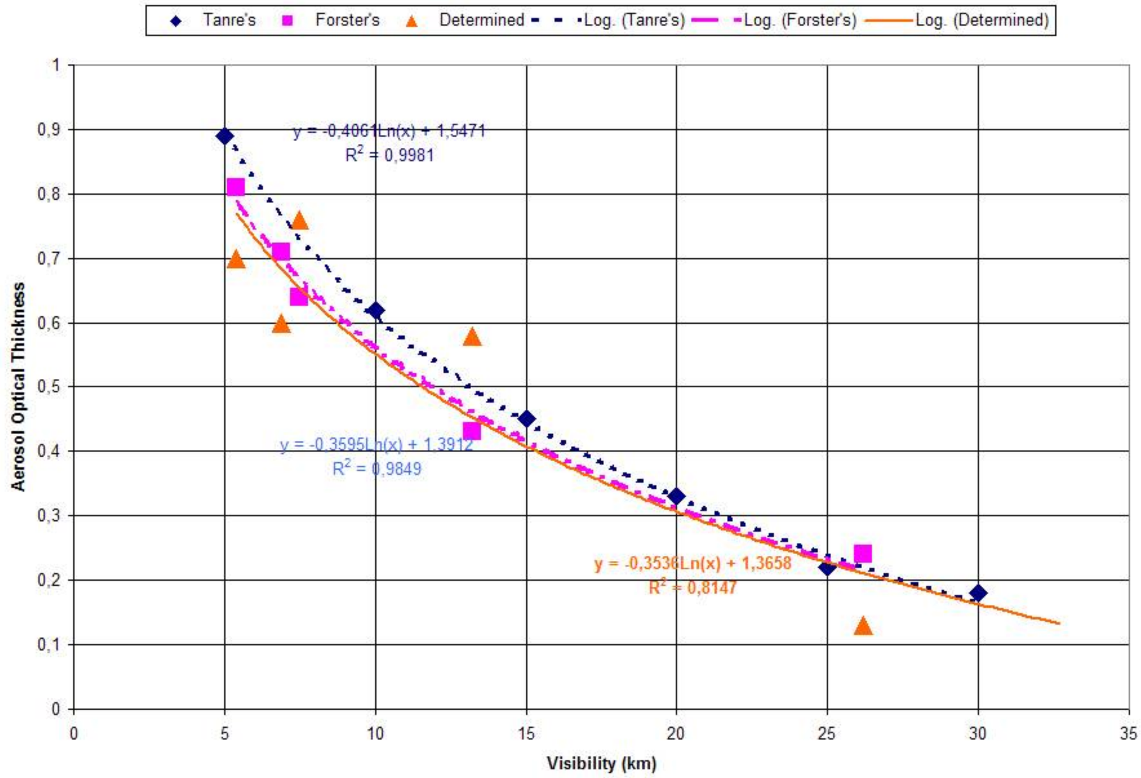


Figure 3. Aerosol optical thickness against visibility (km).

The values of the determined aerosol optical thickness as shown in Table 1 for the images acquired on 28/9/85, 28/6/86 and 4/7/85 have not been fully high-correlated with the visibility data (see deviations in Figure 3) due to the possible impact of the water vapour. The relative humidity data acquired during the satellite overpass can be used to extract useful information regarding the water vapour thickness value as shown by Forster (1984) [2]. Indeed, for the image acquired on 28/9/85 the high RH =68.4 % value may affect the value of the determined aerosol optical thickness.

5.2 Paphos District area: Cyprus

The proposed approach was applied to: (a) Landsat-5 TM band 1 images of the Paphos Airport area acquired on the 11/5/2000, 11/9/98 and 3/6/1985 (b) IKONOS image of Paphos acquired on the 14/3/2000 and (c) SPOT-5 image acquired on 11/4/2003. A positive high correlation of r^2=0.94 between the visibility data measured at Paphos Airport and the deduced aerosol optical thickness for each Landsat TM image. This clearly indicates the potential of the proposed method for assessing the prevailing atmospheric conditions. It is apparent that a hazy atmosphere was occurred on the 3rd of June 1985 (visibility=15 km); and clear atmospheric conditions were found for the 11th of May

2000 (30 km). For the IKONOS and SPOT band 1 images, the determined aerosol optical thickness was 0.20 and 0.18 respectively.

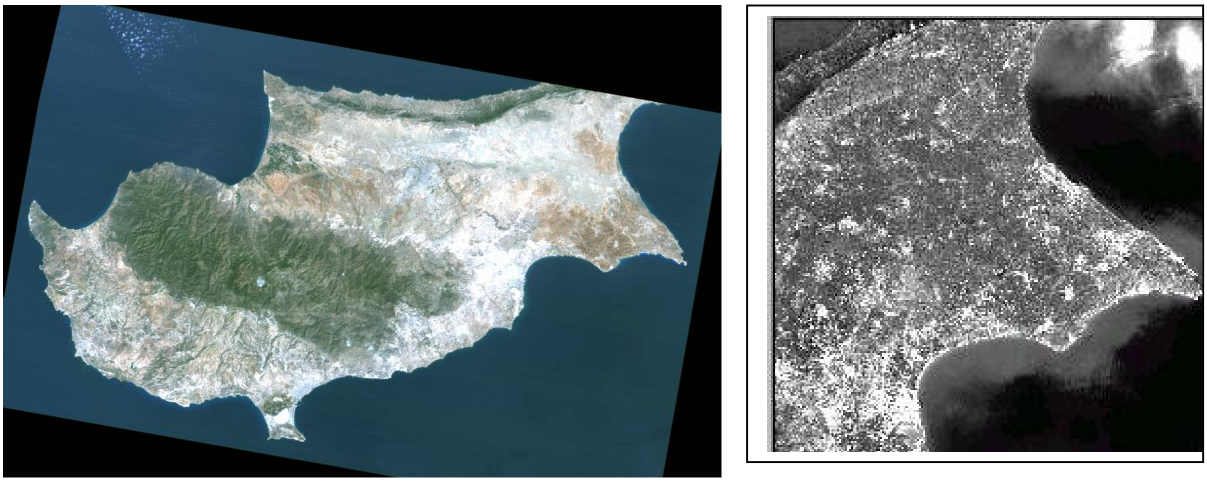


Figure 4: (a) Landsat TM image of Cyprus (11/9/98) (b) Spot 5 image of Cyprus, partial scene (11/4/2003)

6. CONCLUSIONS

The proposed 'modified method' shows how to determine the aerosol optical thickness for a certain area of interest using only the image itself. The method is based on the use of the darkest pixel atmospheric correction theory as well the use of contrast values for selecting the suitable ground reflectance value for the selected dark object. It has been shown that determined aerosol optical thickness in the Heathrow area is highly correlated to the visibility data acquired at the time of satellite overpass. The linear-logarithmic plot between the aerosol optical thickness *Vs* the visibility data agrees with those presented in the literature such as Forster (1984) and Tanre et al. (1979 & 1990). Indeed, this plot can be used as a reference one in order to test and check the determined aerosol optical thickness for future acquisitions.

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