The development of air quality indices through image-retrieved AOT and PM$_{10}$ measurements in Limassol Cyprus

Kyriacos Themistocleous*,a, Diofantos G. Hadjimitsis*,a, Adrianos Retalis,b, Nektarios Chrysoulakisc

a Department of Civil Engineering and Geomatics, Cyprus University of Technology, 31 Archbishop Kyprianos St., 3036 Limassol, Cyprus
b Institute of Environmental Research and Sustainable Development, National Observatory of Athens, Greece, I. Metaxa and Vas. Pavlou, Lofos Koufou, GR 152 36, Palaia Penteli, Athens, Greece
c Institute of Applied and Computational Mathematics, Foundation for Research and Technology - Hellas, N. Plastira 100, Vassiliki Vouton, GR 700 13 Heraklion, Crete, Greece

ABSTRACT

Research indicates that aerosol optical thickness (AOT) values and particulate matter (PM$_{10}$) measurements can be used as indicators of atmospheric pollution. The problem of relating AOT with suspended particulate matter near the ground is still an open question. While satellite images can provide reliable and synoptic measurements from space, comparisons with monitoring surface level air pollution continues to be a challenge since satellite measurements are column-integrated quantities. In this study, in-situ spectroradiometric measurements were taken during satellite overpass using field spectrometers to obtain the reflectance values of the considered calibration targets used. Sun photometer measurements were taken with the Microtops hand-held sun photometer to measure AOT. Meteorological data was collected from nearby meteorological stations and PM$_{10}$ measurements were collected from local mobile air pollution stations. Following, the darkest pixel method of atmospheric correction was applied to a series of Landsat satellite images. The reflectance values of the atmospherically-corrected image were used in the radiative transfer equation to solve for AOT. Thematic maps were generated in order to develop air quality indices. The image-derived AOT values were examined for a positive correlation with PM$_{10}$ measurements. It appears that there exists a strong correlation between AOT and PM$_{10}$ measurements.

Keywords: Aerosol optical thickness, particulate matter, spectroscopy, atmospheric correction, air pollution

1. INTRODUCTION

Air pollution has received considerable attention by local and global communities. Satellite remote sensing can be an effective tool for assessing and mapping air pollution as satellite images are able to provide synoptic views of large areas in one image on a systematic basis. The key parameter for assessing atmospheric pollution in air pollution studies is the aerosol optical thickness. Aerosol optical thickness (AOT) is a measure of aerosol loading in the atmosphere. High AOT values suggest high concentration of aerosols. Particulate matter (PM) consists of very small liquid and solid particles floating in the air. PM$_{10}$ particles are less than 10 microns in diameter. According to the European Directive 2008/50/EC for the quality of air in Europe, the threshold for PM$_{10}$ should not exceed 50 µg/m$^3$ more than 35 times within a twelve month period (http://www.airquality.dli.mlsi.gov.cy). Several researchers have examined the relationship between AOT and PM$_{10}$ measurements as indicators of atmospheric pollution. GIS provide an effective tool to produce air pollution maps using aerosol optical thickness obtained from satellite imagery.

In this study, the objectives are to monitor the air quality (and on a long term basis the quality of life and health of all Cyprus’s citizens), to identify sources of air pollution in order to reduce level of pollution in the atmosphere through targeted measures, to identify local emission sources in the city of Limassol, Cyprus, including construction sites, industrial areas, and high-traffic intersections and to conduct a statistical analysis between PM$_{10}$ and AOT.

*k.themistocleous; phone +35799570178; fax +357-363141, email: k.themistocleous@cut.ac.cy;
2. GIS

GIS has the advantage of the high power of analysing of spatial data and handling large spatial databases. Indeed, in air pollution there are a large amount of data that GIS can be used for their handling. Data that is used for air pollution studies is air pollutants, wind direction, wind speed, traffic flow, solar radiation, air temperature, mixing height etc. The integration of both GIS and remote sensing provides an efficient tool for the air pollution monitoring authorities. With GIS, remote sensing data can be integrated with other types of digital data, such as air pollution measures. Merging satellite remote sensing and GIS tools provides a quick and cost effective way to provide an improved qualitative assessment of pollution. GIS is a tool that can be used for assessing the air pollution through the use of AOT values retrieved directly from satellite imagery or in-situ sun-photometers, from air pollution measurements including CO₂, CO, SO₂, PM10 and other environmental data. The integration of the above information can be inserted into a GIS software which can monitor and map high risk areas resulting air pollution. By using the AOT values retrieved from satellite, a thematic map can be developed through the application of Kriging algorithm in order to indicate high-polluted areas. Based on the determined AOT over an area of interest, and through interpolation, thematic maps can be generated using colour themes showing the levels of the AOT and/or pollution. Such information can be used as a tool for decision-makers to address air quality and environmental issues more effectively. Several studies showed the importance of using both GIS tools as well as satellite remotely sensed imagery to view and analyze the concentration of air pollutants and linkages with land cover and land use.

3. METHODOLOGY

One of the areas of interest for the ‘PM3’ project area is the Limassol District (Cyprus) (Figure 1) Limassol is located on the south-west coast of Cyprus. It is important to highlight that the Cimel sun-photometer (part of AERONET Network) is located at the Cyprus University of Technology, in the center of the Limassol city.

![Figure 1. Study area-Limassol Cyprus.](image)

The resources used in this study included local mobile air pollution stations from the Ministry of Labour and Social Insurance, Department of Labour Inspection, which were used to collect PM10 measurements near the center of Limassol (Figure 2).
Landsat 5 TMand Landsat 7 ETM+ satellite images were also used for this study. The study area is unaffected by the failure of the Landsat ETM+ Scan Line Corrector (SLC); therefore, the satellite image data is of the same quality as data collected prior to the SLC failure (http://landsat.usgs.gov/products_slcoffbackground.php). In order to measure aerosol optical thickness, the Cimel and Microtop sun-photometers were used (Figure 3). The CIMEL sun-tracking photometer measures sun and sky luminance in visible and near-infrared. The MICROTOPS II is a hand-held multi-band sun photometer. The sun-photometer measures the aerosol optical thickness (440 nm, 675 nm, 870 nm, 936 nm and 1020 nm bands) and precipitable water (936nm and 1020nm bands) through the intensity of direct sunlight.

The overall methodology used in this study is illustrated in Figure 4. In this study, Aerosol Optical Thickness (AOT) values derived from satellite images were used to identify sources of air pollution. AOT is the wavelength dependent measure of the total extinction of sunlight due to scattering and absorption by aerosols. In order to retrieve AOT from satellite images, the fast atmospheric correction algorithm developed by Themistocleous et al. 20, 23 was used. This algorithm is an effective image-based atmospheric correction method based on the radiative transfer equation and the improved darkest pixel method of atmospheric correction using non-variant targets 21, 23. In the fast atmospheric...
correction algorithm, the in-situ reflectance data of the non-variant targets established as calibration targets in the Limassol area were used in order to atmospherically correct the image with the improved darkest pixel method \cite{20, 23}. The radiative transfer equations are then used to solve for AOT\cite{20}.

![Overall Methodology adopted in this study](image)

GIS maps were used to assess air pollution levels and verify local emission sources\cite{22}. By using the AOT values retrieved from satellite, a thematic map was developed through the application of Kriging algorithm in order to indicate high-polluted areas, according to the methodology outlined by Themistocleous et al.\cite{22, 23}. The Kriging method of interpolation was used to estimate the AOT values on the GIS map. Using the AOT values derived from the fast atmospheric correction algorithm and interpolation, thematic maps were generated showing the levels of the AOT\cite{22, 23}. The thematic map was overlaid with GIS vector data which included roads, plots and municipality boundaries, to make it easier to identify sources of AOT values within the city and the local municipalities. Following, AOT values and PM10 measurements were assessed. The AOT values derived from the fast atmospheric correction algorithm were assessed with the in-situ AOT values from the Microtops and Cimel sun photometers. The PM10 levels were determined from the air quality monitoring stations from the Department of Labor. Following, a comparison was conducted of the AOT measurements from the air quality monitoring stations with the PM10 measurements recorded by the air quality monitoring stations. The AOT measurements were compared to the PM10 measurements that corresponded to the time of the satellite overpass.

4. FAST ATMOSPHERIC CORRECTION ALGORITHM FOR GIS MODELING

Due to the complexity of the RT equations and their logarithmic components, it was necessary to simplify the fast atmospheric correction algorithm equation developed by Themistocleous et al.\cite{20, 23}, in order to use it to retrieve AOT and conduct a GIS analysis. Equation 1 \((L_p = L_{pr} + L_{pa})\) was reconfigured into a simplified equation which could be solved in MATLAB and ERDAS Imagine. The simplified equation used image based techniques to retrieve AOT values and model them into a GIS geospatial database. In order to display AOT, a Kriging method was used to overlay the data into GIS vector maps of the city to display a spatial distribution of AOT.

It was necessary to transform the fast atmospheric correction algorithm to retrieve AOT values from the satellite image. This was achieved by creating a model and solving the RT equation using a second order equation and solving it using the MacLaurin Taylor series. The MacLaurin Taylor series was used in order to approximate a definite integral to a desired accuracy\cite{24-26}. This simplified algorithm is called the "fast atmospheric correction algorithm for GIS modeling". In order to run the algorithm for each satellite image, the corresponding parameters of phase function, single scattering albedo, and solar zenith angle were used depending on the date of image capture, as well as the radiance and corrected reflectance values. The equation used the parameters of \(L_{ts}, \rho_{tg}, L_{pr}, A, B, \delta, \) and \(\lambda\) that were derived through Mat Lab using the equations discussed below and the values were inserted into the model. In order to develop fast atmospheric correction algorithm for GIS modeling, several equations were rewritten so they could be entered into the MATLAB and ERDAS Imagine model.
The equation was solved for the positive and negative sign so that only AOT values between 0-4.0 would be calculated, which preclude the AOT found on the planet. The equation was inserted and processed through the MATLAB program. The methodology was used to create GIS maps with the AOT values derived from the fast atmospheric correction algorithm. The fast atmospheric correction algorithm was reconfigured to remove the exponents and power functions related to AOT retrieval in order to calculate the AOT values for every pixel in the satellite image and display them in a geo-reference GIS map with points consisting of AOT values. This provided the ability to solve for AOT by using a simplified equation based on the RT equations. In order to conduct the GIS analysis, the “fast atmospheric correction algorithm for GIS modeling” model was developed in MATLAB, ERDAS Imagine 2011 and ArcGIS, as indicated in Figure 5.

Figure 5. Fast Atmospheric Correction Algorithm for GIS modeling developed in ERDAS Imagine 2011
The model was run in MATLAB and ERDAS Imagine 2011 to generate an image comprised of AOT values. Only near-Lambertian dark targets from the satellite image were used to run the model. The model was applied to all dark surfaces in the Landsat band 1 satellite image (since the AOT required were 500 nm wavelength) and an image was created showing the AOT values for every pixel in the image, as indicated in Figure 6. The geo-reference image displayed the map of Limassol that met the criteria defined by the algorithm. The white areas are displayed as having no data, due to high reflectance values of the surface, cloud presence, or surfaces that cannot be solved by the algorithm, such as non-Lambertian targets. All AOT values were exported to ASCII files to create an AOT dataset in order to exclude all the non-data values, which was then imported into ArcGIS.

![Image](image.png)

**Figure 6. AOT values derived from algorithm**

By using the ArcGIS software, each pixel was converted to a point creating an AOT dataset associated with each point. The algorithm calculated only Lambertian or near-Lambertian surfaces, such as roads, parking lots and open areas. Non-Lambertian surfaces, such as buildings, were subtracted prior to the export of the image. Each point is linked with the AOT database with a specific AOT value. The white area consists of values with "no data" (figure 7).
In order to create a GIS thematic map featuring AOT distribution throughout Limassol, interpolation was required that estimated the values missing from the "no data" area. To do so, the ordinary Kriging interpolation tool was used. The AOT dataset was calculated using Kriging, and ordinary Kriging was used, where the weighted average of neighboring samples was used to estimate the unknown values of the “no data” area. The spherical semivariogram model was used in order to depict the spatial autocorrelation of the measured sample points. Figure 8 shows the results of the Kriging interpolation for the Tsireon Stadium area. The dots indicate the points with AOT values, while the colored sections are the AOT values determined from Kriging interpolation.
Following the Kriging interpolation, a thematic map was generated. The map was classified according to AOT values, using different colors for the specified AOT range and a legend of the AOT values was generated. This facilitates the ability to see high and low AOT values, which makes it possible to identify high AOT levels. Figure 9 indicates the map of Limassol as a result of Kriging, which makes possible synoptic views of the AOT distribution.

Figure 9. Thematic map of Limassol (2/5/2011) after Kriging interpolation, with AOT values

The thematic map was overlaid with GIS vector data from the Lands and Surveys Department for Limassol, which included roads, plots and municipality boundaries, to make it easier to identify sources of AOT values within the city and the local municipalities (figure 10). The fast atmospheric correction algorithm for GIS modeling was used to produce GIS maps indicating the AOT distribution over Limassol. A thematic map was generated using different colors for the specified AOT range, which provided the ability to see high and low AOT values. The AOT values generated were compared with the in-situ AOT values from the Microtops and Cimel sun photometers at the five pseudo-invariant targets and at the Cyprus University of Technology, where the Cimel sun photometer is located. A separate thematic map was created for each of the eleven Landsat 5 and Landsat 7 satellite images.
Figure 11 indicates the GIS map using Landsat 7 satellite imagery from 13/4/2010, featuring specific areas targeted for assessing AOT and PM$_{10}$ measurements. In figure 11, the lowest levels of AOT values in Limassol were located at the Tsireon Stadium (#1) and the Laniteon complex (#2) which are primary green, open areas. Both of these areas consistently display low levels of AOT. The highest AOT levels were present in the industrial areas (#3), the CUT campus (#4) and the Limassol Port (#5). Area #3 is the Linopetra industrial estate, which consists of light industry. Area #4 is the Cyprus University of Technology (CUT) which is located in the center of Limassol and experiences road congestion. Area #5 is the Limassol port, which is the main port in Cyprus. From examination of the maps, it is evident that Areas #3 #4 and #5 consistently have high AOT levels in comparison with Areas #1 and #2. The AOT level reported by the Cimel sun photometer located at the Cyprus University of Technology (at 500 nm) is 0.256. The PM$_{10}$ measurements reported by the Department of Labor for Limassol (http://www.airquality.dli.mlsi.gov.cy/) that day were 35.96 $\mu$g/m$^3$. Overall, the map indicates moderate AOT levels, which are supported by the moderate levels of PM$_{10}$ measurements.
The fast atmospheric correction algorithm for GIS modeling was used to produce GIS maps indicating the AOT distribution over Limassol. A thematic map was generated using different colors for the specified AOT range, which provided the ability to see high and low AOT values (Figure 11). The AOT values generated were compared with the in-situ AOT values from the Microtops and Cimel sun photometers at the five pseudo-invariant targets and at the Cyprus University of Technology, where the Cimel sun photometer is located. As research indicates a relationship between AOT values and PM$_{10}$ measurements to determine air quality, a comparison was conducted of the AOT measurements from the air quality monitoring stations with the PM$_{10}$ measurements recorded by the air quality monitoring stations, as this data was available to the author. The AOT measurements were assessed with the PM$_{10}$ measurements that corresponded to the time of the satellite overpass (see table 1). AOT values can vary significantly from PM$_{10}$ data since AOT values indicate the thickness of the atmosphere, while PM$_{10}$ values are locally distributed. The linear correlation between AOT levels and PM$_{10}$ measurements as indicted in figure 10-17 is promising and can be further studied in future work. To date, several researchers have also found a relationship between AOT values and PM$_{10}$ measurements.

Table 3. Comparison table of AOT and PM$_{10}$ measurements

<table>
<thead>
<tr>
<th>Date</th>
<th>AOT measurement near air quality monitoring station</th>
<th>PM$_{10}$ measurement in µg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13/4/2010</td>
<td>0.259</td>
<td>35.96</td>
</tr>
<tr>
<td>29/4/2010</td>
<td>0.276</td>
<td>38.26</td>
</tr>
<tr>
<td>31/5/2010</td>
<td>0.337</td>
<td>45.5</td>
</tr>
<tr>
<td>16/6/2010</td>
<td>0.358</td>
<td>49.84</td>
</tr>
</tbody>
</table>
Relationship between AOT and PM10

\[ y = 0.005x + 0.067 \]

\[ R^2 = 0.813 \]

<table>
<thead>
<tr>
<th>Date</th>
<th>AOT</th>
<th>PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>24/6/2010</td>
<td>0.224</td>
<td>32.26</td>
</tr>
<tr>
<td>10/7/2010</td>
<td>0.274</td>
<td>38.23</td>
</tr>
<tr>
<td>27/8/2010</td>
<td>0.341</td>
<td>54.91</td>
</tr>
<tr>
<td>28/9/2010</td>
<td>0.273</td>
<td>43.37</td>
</tr>
<tr>
<td>7/11/2010</td>
<td>0.317</td>
<td>51.0</td>
</tr>
<tr>
<td>9/12/2010</td>
<td>0.320</td>
<td>47.31</td>
</tr>
<tr>
<td>2/5/2011</td>
<td>0.331</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 12. Linear regression of AOT and PM10 measurements

5. CONCLUSIONS

Earth observations made by satellite sensors are likely to be a valuable tool for monitoring and mapping air pollution due to their major benefit of providing complete and synoptic views of large areas in one snap-shot. Blending together GIS and remote sensing, AOT values can derived over a large area of interest systematically. GIS is used also to map air pollutants based on ground and satellite-derived AOT values. The fast atmospheric correction algorithm for GIS modeling was developed in order to produce a GIS map with the AOT value distribution over Limassol. The study found that by using the AOT values from Landsat, a GIS map with high-polluted areas can be produced. The AOT values derived from the algorithm were compared with the in-situ AOT values from the Microtops and Cimel sun photometer. To further validate the method, values of aerosol optical thickness from the fast atmospheric correction algorithm were compared with those from the hand-held sunphotometer. Further, the obtained strong agreement between the in-situ AOT measurements and the derived AOT values indicated the good accuracy of the algorithm. The algorithm can be considered an effective alternative to the more complex and sophisticated methods as for use with archival data where meteorological or atmospheric input data are not available.

ACKNOWLEDGEMENTS

This study was conducted as part of the LIFE09 ENV/CY/000252-PM3 study and is supported by the European Commission under the LIFE+ Environment and Governance Programme and as part of the project "Air Pollution
Monitoring from Space in Cyprus – AIRSPACE” which is funded by the Cyprus Research Promotion Foundation. The methodology and data presented in this study are from Kyriacos Themistocleous's PhD thesis entitled "Improving atmospheric correction methods for aerosol optical thickness retrieval supported by in-situ observations and GIS analysis”.

REFERENCES

[23] Themistocleous, K., "Improving atmospheric correction methods for aerosol optical thickness retrieval supported by in-situ observations and GIS analysis". PhD Thesis, Cyprus University of Technology, Department of Civil Engineering and Geomatics, (2012).