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Comparative Study of Algorithms for Obtaining AOD Using High Spatial Resolution Satellite Imagery †

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Abstract: Air pollution control and air quality monitoring are global priority, which also applies to local scales. Ground-based monitoring stations provide high quality values, but their number and cost make them insufficient for use at certain scales and for air monitoring in urban areas. Satellite imagery provides indicators directly related to air quality. Aerosol optical thickness (AOD), used in atmospheric corrections of images, can be used as an indicator of air quality. This product is present in images obtained by satellites of medium spatial resolution, so it is necessary to develop methodologies to obtain it at higher resolution. This work aims to compare methodologies for obtaining AOD and its use in high spatial resolution satellites.

Keywords: AOD; pollution; air quality; aerosols; surface reflectance

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1. Introduction

Air pollution causes health problems for millions of people, so the study and control of pollution, which affects air quality, is a priority worldwide. Each country, region or city establishes its own mechanisms to monitor air quality by means of ground stations which, given their high cost, are installed in a small number of places and are insufficient to evaluate the quality of the air breathed by the population. Satellite images represent a source of information that provides continuous data in space and allows periodic monitoring of the territory [1].

However, the spatial resolutions of these images (approx. 1 km), valid at regional or global scales, do not allow effective pollution monitoring over urban areas where large changes are recorded, so it is necessary to resort to high-spatial-resolution images (between 20 and 60 m). The problem of loss of temporal resolution is solved by combining different satellites.

Using remote sensing, it is possible to estimate different types of pollutants: nitrogen dioxide (NO_2), particulate matter (PM), ozone (O_3), sulfur dioxide (SO_2) and aerosol optical thickness (AOD), among others. The concentration of AOD is considered a very important indicator in pollution studies and is the main cause of negative effects on human health. AOD is a measure of the scattering and absorption of visible light produced by particles present in a vertical column, so it is proportional to the concentration of atmospheric particles and is used to measure air quality. This parameter is measured with great precision from stations distributed all over the world, but they are point measurements with limited spatial coverage. In addition, in urban areas, there is a large spatial and temporal variation in AOD, so high-spatial-resolution satellites with near real-time full coverage are important for monitoring.

This paper compares four research works carried out by four different research teams. Their choice, made for their novelty and good results, places all the studies in China, an understandable situation since China is experiencing serious pollution problems, and its capital Beijing is a reference in the field of air pollution research.

2. Methodology for Obtaining AOD

Atmospheric corrections are intended to eliminate or reduce the effect that the passage through the atmosphere has on the electromagnetic radiation reaching the satellite. The absorption and scattering phenomena that occur in the atmosphere are caused by the gases and particles that are found there, so it is necessary to know the composition of the atmosphere at the time of image acquisition. The phenomena produced by gases (ozone, oxygen, etc.) are easily corrected due to their spatial and temporal stability. However, this is not the case for aerosols and water vapor, whose estimation is complicated. Atmospheric correction models include, among other parameters, the value of aerosol optical thickness (AOD), and this situation serves as a starting point for AOD retrieval in images of higher spatial resolution [2].

By means of an atmospheric correction, the reflectance of the upper atmosphere (ϱTOA), captured by satellite sensors, can be transformed into surface reflectance (ϱSUP) through the radiative transfer Equation (1) that assesses the scattering and absorption occurring in the atmosphere.

$$\varrho\mathrm{TOA} = \varrho\mathrm{a}(\theta\mathrm{s}, \theta\mathrm{v}, \phi) + \mathrm{T}(\theta\mathrm{s})\mathrm{T}(\theta\mathrm{v})\varrho\mathrm{SUP}/[1 - \varrho\mathrm{SUPS}] \quad (1)$$

where ϱTOA is the reflectance at the satellite, ϱSUP is the surface reflectance, θs and θv are the solar and sensor zenith angle, ϕ is the relative azimuthal angle between the solar direction and the sensor, ϱa is the intrinsic reflectivity of the atmosphere, T is the transmission for the entire atmospheric layer, and S is the atmospheric backscattering ratio at the bottom of the atmosphere.

If the process is reversed and the reflectance captured by the sensor (ϱTOA) and the surface reflectance (ϱSUP) are known, the optical thickness of the atmosphere can be determined. For this purpose, interpolation tables (LUT), generated by the radiative transfer Equation (1), are used to collect the relationship between the two reflectances and the AOD for a given wavelength [3].

The phases followed in obtaining the AOD are summarized as follows:

1. Obtaining clean images of clouds, ice and snow. Clouds, cloud shadows, ice, snow and water sheets are treated as invalid pixels and are removed by using masks to avoid significant errors in the AOD calculation.
2. Surface classification and calculation of surface reflectances. This section is the starting point for AOD recovery and is therefore one of the most sensitive phases of the methodology.
3. Identification of aerosol types. The asymmetric factor (G) and the single scattering albedo (SSA) are the main parameters that best define the scattering effects caused by aerosols. They define each aerosol type and vary with time and location.
4. AOD interpolation through LUT tables.

In this process, the elements that determine the accuracy in estimating the AOD are the calculation of surface reflectance and the assumption of aerosol types.

3. Surface Reflectivity Calculation

One of the input parameters for AOD calculation through satellite images is the surface reflectivity. The accuracy of its determination directly influences the estimated AOD value. Several methods have been developed for its accurate estimation.

3.1. Methods Based on Spectral Characteristics

3.1.1. Dark Object Subtration (DOS)

The use of this method requires the existence of dark objects in the image. The surface reflectance (ϱSUP) of the dark areas is close to 0, while the reflectances on the sensor (ϱTOAs) acquire values other than 0, which are the result of the passage of radiation through the atmosphere, (ϱa = ϱTOA). To calculate the surface reflectance (ϱSUP), the ϱTOA obtained in the dark pixels of the image is subtracted from all the pixels of the image. This method assumes that the atmosphere is spatially uniform over the image.

3.1.2. Dark target (DT)

This method is based on the fact that the atmosphere hardly affects the apparent reflectance (ϱTOA) of a dark object (e.g., dense vegetation) in the Mid-IR band (2.11 µm), so the apparent reflectance of that object in that band is practically equal to its surface reflectance (ϱSUP). It also uses the relationship between the reflectance of the mid-IR band and the reflectance of the blue and red bands. From here, when taking an image, the Mid-IR band will allow the calculation of the surface reflectance in the blue and red bands. This method has the drawback that it is only possible to calculate the surface reflectivity in areas of dense vegetation where it is widely used [4,5].

There is a variation of the method that consists of using the near infrared band (NIR, 0.85 µm) instead of Mid-IR in those satellites that do not have this band. The linear relationship between this band and the red band is also established.

3.1.3. Deep Blue (DB)

This is a method similar to DT, except that this algorithm allows the calculation of surface reflectance in areas that reflect light, such as desert, semi-arid and urban regions. The method is based on the characteristics of the "deep blue" band (0.412 µm). In this band, values due to aerosols (which tend to be high) are well differentiated from surface reflectance (with lower values, between 0 and 0.1). This method allows higher spatial coverage compared to the DT method, which is only valid for dark surfaces [6].

3.2. Methods Based on Multi-Temporal Information

3.2.1. Minimum Reflectance Method (MRT)

In the last decade, thanks to the improved accessibility of image databases, the possibility of combining information between images from different sensors and the emergence of platforms and resources that allow the analysis of large amounts of information, methodologies based on time series have been developed. These methods assume that the surface reflectance is constant over a given time interval and that only some of the pixel values are significantly affected by aerosols.

The method consists of constructing images (MRT) where each pixel (time invariant) stores the lowest value of a large time series. To avoid errors caused by shadows or clouds, the methodology is sometimes modified by selecting the second lowest value. An MRT image is made for each time of the year.

3.2.2. LaSRC (Land Surface Reflectance Code)

The large collection of images collected by MODIS allowed the development of a methodology for obtaining surface reflectance, which is applied in the atmospheric correction of images from other satellites such as Landsat 8 and, recently, Sentinel 2 [7].

The scheme for obtaining the surface reflectance is based on the strong spectral relationships between the red and blue bands and the relationship between red and mid-infrared. To parameterize this relationship, an adjustment was made based on the images obtained during 10 years in these bands by the MODIS Terra sensor. Subsequently, they were atmospherically corrected with MISR AOT data and cloud pixels, and pixels with high AOT values were removed. The surface reflectances of each band were compared to obtain the equation relating them and the relationships between the spectral ratios and the $NDVI_{MIR}$

index (little influenced by aerosols and therefore more useful for characterizing the surface) were obtained.

From these spectral ratios extracted from time series, it is possible to calculate surface reflectance from data from other satellites such as Landsat 8 or Sentinel 2.

4. Definition of Aerosol Typology

Along with surface reflectance, the definition of the aerosol model is another critical factor in accurately estimating AOD. The 6SV model classifies aerosols into five types, although it can be adjusted to user-determined parameters from in situ measurements. The five models are: the continental model, the maritime model, the urban model, the desert model and the biomass-burning smoke model. Generally speaking, they are sufficient for the description of aerosols over the entire planet [7].

5. Comparison

Table 1 provides a comparison of the AOD recovery works according to the methodology used in the definition of surface reflectance, the aerosol models used and the accuracy obtained against the observations of AERONET stations.

Table 1. AOD procurement procedures.

Authors Research	Li et al. [8]	Lin et al. [9]	Lin et al. [10]	Yang et al. [11]	Jin et al. [12]
Satellite	Landsat8 Sentinel2A	Landsat-8	Landsat8 Sentinel2A	Landsat-8	Landsat8 Sentinel2A
Surfaces	Unspecified	densely veg sparse veg. barely non-veg.	-densely veg. (DVA) -sparse veg. (SVA) -barely non-veg. (BVA) -change areas (LCA)	-con veg. (AV) -brilliant (AR)	Unspecified
Surface Reflectance Estimation	LaSRC	DVA: DT BVA: DB SVA: MRT	DVA: DT BVA: DB SVA: MRT LCA: Interpolation	AR: MRT AV: DB	LaSRC
AOD Retrieval	6SV	6SV	6SV	6SV	6SV
Aerosols	Urban Aerosol	4 types	4 types	5 4 types	Urban Aerosol
R^2	0.960	0.920	0.905	0.907	L8 0.707; S2 0.818
RMSD	0.175	0.112	0.119	0.087	L8 0.173; S2 0.138

All the consulted authors manage to retrieve an accurate AOD (close to 0.90 except Jin et al. [12]) from high-spatial-resolution sensors. Most of the studied works classify canopies into three types and apply different surface reflectance calculations for each of them. The evaluated studies combine methods based on the spectral characteristics of the canopy and the atmosphere with methods based on information obtained from multitemporal databases. In all cases, the LUT tables generated by the 6SV model are used. The description of different types of aerosols is included in the model.

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