Remote sensing of atmospheric PM$_{2.5}$ from high spatial resolution image of Chinese environmental satellite HJ-1/CCD data

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Abstract. Due to lack of the middle infrared wavelength, it is difficult to employ the classic dark target method to retrieve aerosol optical depth (AOD) from Chinese Environmental satellite HJ1-CCD data. Therefore, focusing on extracting weak information from mixed satellite signals of atmosphere and land surface, we developed the Multi-wavelength, Multi-sensor, Multi-day (3M) approach in order to utilize maximally the observation information, and with the consideration of a prior knowledge, e.g. the surface property changes quickly with location but slowly with time. We present the AOD retrieval algorithm based on HJ1-CCD blue and green bands, based on the look-up table approach constructed using 6S radiative transfer model to provide the simultaneous determination of AOD and the ground reflectance. The aerosol and particle size information obtained from ground-based sun-sky radiometer are then used to estimate PM$_{2.5}$ on the surface level, while air humidity and height of planetary boundary layer from reanalysis data are employed to improve the correlation between AOD and PM$_{2.5}$. Validation of the retrieval results with different spatial resolutions (300, 500 and 1000 m), are also performed by comparison with ground-based measurements at three sites of North China regions.

1. Introduction
HJ-1/CCD is one of the key instruments onboard Chinese HJ-1 A and B satellites, launched on 6 September 2008. Each satellite has two cameras equipped four bands (430-520, 520-600, 630-690, and 760-900 nm) CCD with spatial resolution of 30 meters. Four CCD cameras can provide a swath of about 700 km wide and a revisiting time of 2 days. The features of wide coverage, high spatial resolution and high revisiting frequency of CCD cameras provide HJ-1 satellites with capability of environmental monitoring.

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PM$_{2.5}$ are suspended atmospheric particles with aerodynamic diameter less than 2.5 micron, which can cause serious health hazards when absorbing harmful materials aggregated in the surface layer near the ground[1], and significantly influence the climate system by reflecting and absorbing solar radiance arriving the earth[2]. These small particles, quickly varied in time and location, are difficult to grasp and greatly require large scale observation capability from space. The satellite observation of the total suspended particles (TSP) has archived significant progress since the lunch of moderate resolution imaging spectrometers (e.g. MODIS), about a dozen years ago. However, the PM$_{2.5}$ remote sensing remains difficult because PM$_{2.5}$ are small particles and refer usually the quantity in the surface level differing from TSP. Moreover, atmospheric pollution caused by PM$_{2.5}$ is paid more and more attentions in the city region, where the spatial distribution of PM$_{2.5}$ are more complex than rural regions. Therefore, there is an important requirement for high spatial resolution remote sensing of PM$_{2.5}$ from space for the purpose of environmental monitoring. However due to lack of the middle infrared wavelength, it is difficult to employ the classic dark target method to retrieve aerosol optical depth (AOD) from HJ-1/CCD data.

In this paper, we retrieved AOD based on the use of HJ1-CCD blue (430-520 nm) and green (520-600 nm) bands without need of auxiliary data, and then estimated the PM$_{2.5}$ with corrections of the relative humidity, vertical distribution and particle size effects.

2. Methodology

We used HJ-1/CCD to derive AOD at 550nm, which is the previous step to estimate PM$_{2.5}$. The accumulation mode fraction (AMF) from ground based sun-sky radiometer CE318 is used to correct particle size effect. The height of planetary boundary layer (HPBL) and relative humidity (RH) obtained from NCEP (National Centers for Environmental Prediction) Final Operational Analysis data are then employed to correct vertical distribution and hygroscopic effects to obtain PM2.5 from satellite AOD measurements.

![Flowchart of the satellite-based PM$_{2.5}$ estimation algorithm.](image)

Figure 1. Flowchart of the satellite-based PM$_{2.5}$ estimation algorithm.

2.1. The AOD retrieval

The AOD retrieval algorithm is based on two assumptions [3]: (i) Aerosol optical properties vary quickly with time but slowly with location; (ii) Surface reflectance varies quickly with location but slowly with time. For two images at different but close times, the difference in the apparent radiance is mostly caused by the changes of aerosols neglecting solar position effects. Using a constant aerosol model with AOD varied from 0.001 to 2, we established the relationship between AOD and satellite signal in the form of Look-up table (LUT). The LUT in this study is precalculated for a given aerosol model using Second Simulation of the Satellite Signal in the Solar Spectrum (6S) code [5, 6]. We then retrieved the AOD by minimizing the surface reflectance difference of satellite images within a certain time window (usually days to weeks). Details are described in [4].

2.2. The AOD-PM$_{2.5}$ conversion
AOD is a parameter for the ensemble of total suspended particles, while PM$_{2.5}$ are particles with aerodynamic diameters less than 2.5 μm. In this paper, we used AMF to correct this particle size effect [7]. Moreover, there can still remain significant difference between remote sensing observation data and in situ measurements performed at surface due to particle’s vertical distribution and hygroscopicity. The correlation between AOD and PM$_{2.5}$, therefore, needs to be corrected by the height of planetary layer [8] and relative humidity [9,10]. In order to build the relationship between AOD and PM$_{2.5}$, we established a simple model to take into account these correction factors:

$$AOD_{\text{sd}} = AOD \cdot \text{AMF} / [F(RH) \cdot \text{HPBL}]$$

where, $F(RH) = (1 - RH/100)^{-1}$, and AOD$_{\text{sd}}$ is aerosol optical depth with particle size, relative humidity and vertical corrections. Based on ground-based measurements (AOD, AMF, RH, HPBL and PM$_{2.5}$) of March 2012 in Tianjin region, we obtain:

$$PM_{2.5} = 314.2 \cdot AOD_{\text{sd}} + 25.1.$$  

2.3. Study area
We chose a study area in Tianjin region of North China, and obtained HJ-1/CCD data on March 14, 2012 (Figure 2). Three ground-based observation sites (Tianjin, Tiangang, Tanggu) are selected to provide validation measurements. We obtain the AMF and reference AOD in different spectral bands from CIMEL sun-sky radiometers (CE318) installed at the validation site.

![Figure 2. The study area (60 × 60 km$^2$ located in Tianjin region, North China). HJ-1 images are obtained on 2012-03-07 at 10:35 AM.](image)

2.4. Data processing
Geometric correction and radiometric calibration were performed to HJ-1/CCD data firstly, and then we subsampled the images to 100 m resolution in order to reduce noise and registration errors and to smooth local variation of surface reflectance. Two HJ-1/CCD spectral bands, centered at 483 and 568 nm, are used in the aerosol retrieval considering these bands are sensitive to aerosol effects, while in most cases the surface reflectance of these bands varies slowly. We considered that AOD is stable in
an area smaller than $300 \times 300 \, \text{m}^2$, and retrieved AOD in three different resolutions of 300, 500 and 1000 m, respectively.

In order to obtain the correlation between AOD and PM$_{2.5}$, the AMF calculated from ground-based radiometer observation $^{[11]}$ and planetary boundary layer height and relative humidity from reanalysis data are used as described in section 2.2. In this study, the AMF is obtained from mean value of three measurement sites while the reanalysis data are obtained from the NCEP FNL with a horizontal resolution of $1^\circ \times 1^\circ$ and temporal resolution of 6 hours. The inverse distance weighted and sinusoidal interpolation methods are used to refine the space and temporal resolution fitting to AOD retrieved from HJ-1A/B, respectively.

2.5. Results

![Figure 3. AOD retrieved from HJ-1/CCD data (2012-03-07, 10:35 AM) in different spatial resolution.](image)

Based on HJ-1 data on 7 March 2012, the spatial AOD images at different resolutions are retrieved and shown in Figure 3. We listed the retrieved AOD (550 nm) values at three validation sites in Table 1. From the comparison with ground-based CE318 measurements, we found that results with resolution of 300 m are the closest to CE318 measurement compared to other two resolutions, which can be explained partly by the natural complexity of spatial variation of aerosols in urban region. The averaged AOD error is 0.042 in 300 m resolution compared with CE318 measurements. We showed also the estimated PM$_{2.5}$ in Table 1. We found that the averaged PM$_{2.5}$ error is about 13 ug cm$^{-3}$ compared with in situ measurements.

| Site   | HJ1 Retrieved AOD | AOD of CE318 | Error in AOD | PM$_{2.5}$ estimated from HJ1 | PM$_{2.5}$ in situ | Error in PM$_{2.5}$ |
|--------|------------------|--------------|--------------|------------------------------|-------------------|--------------------|
|        |                  | 1000 m       | 500 m       | 300 m                       | 1000 m            | 500 m              | 300 m             |
| Tianjin  | 0.400           | 0.240        | 0.240        | 0.362                       | 0.038             | 0.122              | 0.122             |
|        | 0.240           | 0.260        | 0.264        | 0.024                       | 0.024             | 0.004              | 48.2              |
|        | 0.580           | 0.160        | 0.300        | 0.302                       | 0.279             | 0.141              | 0.001             |
|        | 0.407           | 0.214        | 0.267        | 0.309                       | 0.114             | 0.096              | 0.042             |
| Averaged| 0.407           | 0.214        | 0.267        | 0.309                       | 0.114             | 0.096              | 0.042             |

3. Conclusion
The high spatial and temporal resolution of HJ-1/CCD data makes it suitable for environment monitoring. Based on preliminary analyses of AOD and PM\(_{2.5}\) retrieved in North China region, we conclude that:

(i) AOD can be retrieved from the multi-temporal HJ1-CCD data with the use of blue and green bands. For the investigated cases, the AOD retrieval error is about 0.042 at 550 m.

(ii) Relative humidity, aerosol vertical distribution and particle size corrections can be used in the estimate of PM\(_{2.5}\) from satellite observation, which results in about 13 \text{ug m}^{-3} errors for the investigated cases.

(iii) AOD retrieval uncertainty can be decreased with the increase of spatial resolution in the urban regions. However, the observation noise may be rising when employing higher resolution, which will be investigated in the next studies.

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