Retrieval and Validation of Aerosol Optical Depth by using the GF-1 Remote Sensing Data

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Abstract. Based on the characteristics of GF-1 remote sensing data, the method and data processing procedure to retrieve the Aerosol Optical Depth (AOD) are developed in this study. The surface contribution over dense vegetation and urban bright target areas are respectively removed by using the dark target and deep blue algorithms. Our method is applied for the three serious polluted Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD) and Pearl River Delta (PRD) regions. The retrieved AOD are validated by ground-based AERONET data from Beijing, Hangzhou, Hong Kong sites. Our results show that, 1) the heavy aerosol loadings are usually distributed in high industrial emission and dense populated cities, with the AOD value near 1. 2) There is a good agreement between satellite-retrievals and in-site observations, with the coefficient factors of 0.71 (BTH), 0.55 (YRD) and 0.54(PRD). 3) The GF-1 retrieval uncertainties are mainly from the impact of cloud contamination, high surface reflectance and assumed aerosol model.

1. Introduction
Aerosol is a stable mixture of solid particles and liquid particles uniformly dispersed in the atmosphere. Aerosol Optical Depth (AOD) is the integral of the extinction coefficient in the vertical direction, which represents the attenuation of visible light by the whole atmosphere’s aerosol particles. Although the aerosol content in the atmosphere is relatively small, its effect in atmospheric circulation cannot be ignored, affecting the Earth’s climate and ecosystems, leading to decreased visibility on the ground, air quality deterioration, and causing a thread to public health [1]. Accurately obtain the space-time distribution, source and transmission path of aerosol, which is an important guarantee for weighting particulate pollution effect, formulating particulate reduction, prevention and control policies. Aerosol observation mainly rely on conventional instruments such as CE318 automatic tracking solar photometer and Micro Tops-II manual solar photometer, and the aerosol automatic observation network also provides important ground observation data for the research of aerosol radiation characteristics and climate effects in China [2]. However, due to the high cost, complexity of operation and maintenance of ground observation, this routine monitoring can only be carried out at limited ground stations, which cannot meet the requirement of continuous dynamic and macro monitoring of environmental pollution, and cannot reflect the spatial distribution of aerosols over a large area. Satellite remote sensing has the characteristics of large area coverage, quasi-real-time acquisition and dynamic updating. It can quickly and accurately monitor atmospheric pollution, and improve the precision of atmosphere aerosol detection [3].

GF-1 successfully launched by the Long March II Ding launch rocket on April 26, 2013 in Jiuquan Satellite Launch Center, it is the first satellite of the high-resolution Earth observation system of
national science and technology major project, it has a high space resolution (16m), repeat cycle is only 4 days, compare with the world’s similar satellite, whose repeat cycle is mostly more than 10 days, GF-1 has achieve a perfect combination of high spatial resolution and high time resolution. GF-1 can provide high-precision and wide-range space observation services for the agricultural, meteorological and environmental protection departments, and play an important role in geography, oceanography and climate meteorological observation [4].

At present, with the development of research in using satellite remote sensing data to inverse land aerosol, it has formed a relatively complete system. Based on the characteristics of different load, there has been formed some aerosol inversion algorithm, such as single-channel, multi-channel, multi-angle, polarization and others. Many Chinese scholars have also conducted extensive research on aerosol satellite inversion and product application. In the study of inversion algorithms, Li et al. [5] used MODIS data to study aerosols in Beijing area, comparing the two different inversion methods of dark pixel method and structural function method. Li et al. [3] developed a surface reflectivity library algorithm and used it for inversion aerosols in urban and winter vegetation-free area. In terms of the product testing and application, Chen et al. [6] and Wu et al. [7] validate the effectiveness of MODIS aerosol optical depths in the Taiwan Strait and the Taklimakan Desert. In general, the most mature aerosol satellite products developed are based on NASA/MODIS sensors whether at home or abroad, most of the applied research and verification are also carried out for MODIS and MISR data, such as Li et al. [8] Inter-comparison of model-simulated and satellite-retrieved componental aerosol optical depths in China. At present, the research on atmospheric remote sensing for high-resolution satellite remote sensing data has just started. For example, Chinese researcher Wang Zhongtianing developed a land aerosol inversion algorithm based on environment-1 satellite data [9, 10]. In order to make the high-resolution satellite data play an important role in atmospheric monitoring, it is urgent to develop an aerosol optical thickness inversion algorithm based on GF-1 satellite, and evaluate its potential of inversion atmosphere parameters.

This paper mainly uses GF-1 data to develop the inversion process of AOD and validate it with ground data. The first part mainly introduces the data and processing operation used in this paper; the second part detailed elaborates the inversion algorithm and the flow; in the third part, the results are applied to Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD) and Pearl River Delta (PRD) where the pollution is more serious, and then compared with ground AERONET data, finally, display the conclusion.

2. Data introduction

The Ministry of Environmental Protection Satellite Environment Application Center received the original date of GF-1, those used as satellite data, including four band tiff files, rpb files, which uses to carry out geometric correction. Due to the data in 2014 is abundant and the quality is relatively stable, we extracted the original documents in 2014, through the inversion algorithm processing, then obtained the AOD results.

AERONET (Aerosol Robotic Network) is a ground-based aerosol observational network jointly established by NASA and LOA-PHOTONS (CNRS), currently there are more than 500 sites in the world, covering almost all the major regions in the world. There are about 32 observation sites in China; this paper downloaded the 2014’s Level2.0 observations of all the stations. Due to the difficulties in station maintenance and complicated data correction, since 2014 in China, only Beijing (including Beijing and Xianghe stations), Hangzhou, Hangzhou and Hong Kong, the data is relatively perfect.

In order to match satellite data with ground-based observations, we have done the following processes: Based on the GF-1 transit time, we take ground observation one hour before and after to match it, obtain the average daily results. Using the AOD and Angstrom indices at 440 nm and 870 nm, obtain the AOD at 550 nm by interpolation. Based on the ground-based observation station’s center latitude and longitude, extract the corresponding AOD value in satellite file within 50 km.

3. Retrieval principle and process
3.1. Dark pixel and dark blue algorithm based on GF-1 / AOD

When using the variable method for land aerosol inversion, assume the ground surface is Lambertian, atmospheric water vapor is evenly distributed, and the satellite received radiation can be expressed as [11]:

\[
L(\mu_s) = L_0(\mu_s) + \frac{r}{1 - rS} \mu_s F_\theta T(\mu_s) T(\mu_s)
\] (1)

In the formula (1), \( \mu_s = \cos \theta_s \), \( \mu_v = \cos \theta_v \). The \( \theta_s \) means the solar zenith angle, the \( \theta_v \) means the observation zenith angle. The \( L_0(\mu_s) \) means radiation of the obverse direction path. The \( r \) means Lambertian surface reflectivity. The \( S \) means hemispheric reflectivity of the lower atmosphere. The \( T \) means atmospheric transmittance. The \( \mu S F_\theta \) means radiation flux density, in the direction of the top of the atmosphere perpendicular to the solar. Normalization of the formula (1) can obtain the top reflectivity of the atmosphere \( \rho_{TH} \):

\[
\rho_{TH}(\mu_s, \mu_v, \phi) = T(\mu_s) T(\mu_v) \rho_s(\mu_s, \mu_v, \phi) / [1 - \rho_s(\mu_s, \mu_v, \phi) S] + \rho_0(\mu_v, \mu_s, \phi)
\] (2)

In the formula (2), the \( \rho_0 \) means equivalent reflectance of radiation in the atmosphere path. The \( \rho_s \) means surface two-dimensional reflectivity. The \( \phi \) means relative azimuth angle. Due to the different aerosol optical thicknesses have different numerical values in \( S \) . \( \rho_0 \) and \( T(\mu_s) T(\mu_v) \). Using the relationship between these variables, we can deduce the aerosol optical thickness from satellite observations, but the premise process is ground-air decoupling.

Ground-air decoupling is actually the removal of surface reflected noise. For the vegetation-intensive surface (dark pixels), because the red and blue bands have a smaller reflectivity, and there is red, blue channel reflectivity has a good linear correlation. Therefore, based on the liner relationship between red and blue bands’ surface reflectivity of dark pixels, removing the surface contribution from the apparent reflectivity of the red and blue bands, then obtain the aerosol optical thickness. So, the key to aerosol optical thickness satellite remote sensing retrieval is the identification of dark pixels and the relationship between the red and blue bands [11]. Due to the lack of short-wave near-infrared channels, which is less affected by the atmosphere (Such as 2.1 microns), the GF-1 data are difficult to detect in surface information. In this paper, we select the red and near-infrared bands to construct vegetation index, then use it to identify the dark pixels. Through a large number of ground observation experiments in the North China Plain and research of related literatures [12], in this paper, the dark pixel identification threshold is set to 0.7 and the surface reflectivity relationship between red and blue bands is set to 1.6.

Usually, in urban and winter non-dense vegetation areas, it cannot use the GF-1 vegetation index to identify a wide range of dark targets and to establish an empirical relationship about reflectivity. Hsu et al. [13] proposed a dark blue algorithm; this algorithm establish the surface reflectivity library based on the blue reflectance library, which is less affected by the surface noise, and then inversion AOD of the desert and other high-level surface reflection region. This paper refer this algorithm idea, it is assumed that there is no sudden weather effects such as rainfall and snowfall in a short time, no change in the land cover types in urban and other bright target areas, and little difference in vegetation growth. Using the GF-1 satellite transit time to get the MODIS surface reflectance data, in other words, coupling the MODIS data on the closest time as the real surface reflectivity, to solve the problem about surface reflection noise removal.

3.2. GF-1 / AOD retrieval process

In this paper, the aerosol optical thickness inversion process is shown in figure1:

3.3. Build lookup table references to preprints.

The look-up table is calculated by using 6S software for radiation transmission calculation; it needs to set different satellite observation geometrical parameters, different atmospheric aerosol parameters,
considering the band of the observed data and the different surface types and other parameters. Wherein the observed geometric parameters, there are 9 solar zenith angles of 0°, 6°, 12°, 24°, 35.2°, 48°, 54°, 60° and 66°; there are 12 observation zenith angles from 0° to 66° range, and each observation angle separated by 6°; there are 16 relative azimuth angles between the suns and the satellites in the range of 0° to 180°, and each azimuth angle separated by 12°. Set up six atmospheric aerosol optical thickness values (at the wavelength of 0.55 μm): 0, 0.25, 0.5, 1.0, 1.5 and 2; the central wavelength of the band is initial set as 0.47μm, 0.66μm, and based on the band response function of GF-1 to change.

3.4. Data preprocessing.
Data preprocessing includes calculating the apparent reflectance of 0.47μm and 0.66μm bands from the GF-1 data, simultaneously, reading geometric positioning parameters, such as latitude and longitude, altitude, solar zenith angle, solar azimuth angle, observation zenith Angle, and observation azimuth and other data.

3.5. Pixel recognition.
In this paper, the first step of the aerosol optical thickness inversion algorithm is pixel recognition. Among them, the cloud recognition algorithm is mainly based on the threshold difference of the red, blue, and near-infrared channel apparent reflectance, and compare with the MODIS surface reflectance library. As mentioned above, dense vegetation and urban bright targets and other surface pixel are mainly distinguished by vegetation indices.

3.6. Ground-air decoupling process.
According to the pixel type, the aerosol inversion is not performed in the cloud area. In the dense vegetation area, the surface contribution is removed by the surface reflectivity relation between red and blue bands. In the urban and other bright target area, through the coupling surface reflectivity library, obtain the blue band ground reflectance value of the corresponding latitude and longitude. The surface reflectance library established in this paper is obtained by using the remote sensing software ENVI, processing the 8 days synthetic surface reflectance product of MODIS by extracting band, re-projection, resampling, image cutting and mosaic.

3.7. Calculation of aerosol optical thickness.
Firstly, using the observed geometrical parameters read from GF-1 data and select the closest atmospheric parameters in the look-up table, then perform linear interpolation according to the actual observation geometrical data, and obtain the atmospheric parameters at different wavelengths and aerosol optical thicknesses. Finally, calculate the assumed apparent reflectivity according to formula.

![Figure 1. Aerosol optical thickness retrieval process](image1)

![Figure 2. The annual mean distribution of aerosol optical thickness in Beijing-Tianjin-Hebei in 2014](image2)
(2), and the real aerosol optical thickness is obtained by linear interpolation of the real apparent reflectivity.

![Figure 3. The annual mean distribution of aerosol optical thickness in Yangtze River Delta region in 2014](image)

4. Retrieval results and verification

4.1. Retrieval Results
With the increasingly serious air pollution situation in China, especially Beijing, Tianjin, Yangtze River Delta, Pearl River Delta and other key urban agglomerations appeared serious pollution. In this section, we monitor the aerosol distribution in the three demonstration areas based on GF-1 satellite data in 2014.

Figure 2 shows the annual mean distribution of AOD in Beijing-Tianjin-Hebei in 2014. The aerosol optical thickness shows a pattern of southeast high and northwest low. The results indicate that the distribution of AOD with higher values locate in the Beijing, Tianjin, the south of Hebei, which are core urban areas. The range is around 1. In the contrary, the areas with lower AOD values (<0.5) locate in the west and north region, which are Yanshan Mountains with few human activities and high vegetation coverage. Within the six-ring in Beijing is mainly affected by a large number of living emissions and traffic emissions. Relatively speaking, Tianjin, Hebei and other places mainly because port, industrial emissions and other air pollution.

Based on GF-1 satellite data, figure 3 shows the annual mean distribution of AOD in Yangtze River Delta region in 2014. The results indicate that the distribution of AOD with higher values (>1) are concentrated among three core cities of Shanghai, Nanjing and Hangzhou. This region include
Zhenjiang, Changzhou, Wuxi, Suzhou and other cities and towns which are intensive, manufacturing and industrial emissions of concentrated areas. In addition, Nantong in Jiangsu, Ningbo in Zhejiang, Taizhou and Wenzhou also have a high AOD distribution. Otherwise, the areas with lower AOD values locate in the north of Jiangsu, which is covered with farmland, and the southwest of Zhejiang, which is mountain with high vegetation coverage.

Figure 4 shows the annual mean distribution of AOD in Pearl River Delta region in 2014. The results indicate that the distribution of AOD with higher values locate in the core areas of Hong Kong city clusters such as Foshan, Guangzhou, Dongguan and Zhongshan, which are urban-intensive and manufacturing and industrial emissions are concentrated. With far from the above core areas, the places of AOD with lower values locate in rural and mountains with lower anthropogenic emissions and higher vegetation cover. Through the comparison results of the average annual AOD in Pearl River Delta in 2014, we can conclude that Foshan’s AOD value is highest (>1.1), Zhongshan, Dongguan, Guangzhou and other cities with high level of urbanization also has a high AOD level (~1). In the contrary, the AOD value (~0.7) of Huizhou is lowest because of its highest forest cover rate.

4.2. Results verification
In this paper, we use AERONET Level 2.0 observations from Beijing, Hangzhou and Hong Kong respectively as representatives of Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta, and synthesize three areas as representative of the whole country, and then to verify the inversion results of GF-1 AOD in different areas (figure 5 and table 1).

![Figure 5](image-url)

Figure 5. Comparison of scatter slots of GF-1 AOD and AERONET observations in China and three regions; (a) National (b) Beijing (c) Hangzhou (d) Hong Kong

Figure 5 and Table 1 shows the scatter slots and comparison results of GF-1 AOD and AERONET observations in China, Beijing, Hangzhou and Hong Kong in 2014 respectively. From the Table 1, the results indicate that the correlation coefficient (R2) reaches 0.6 between the ground and the satellite. The inversion range is relatively close. The MAX and MIN values differ by 0.16 and 0.03 respectively. In general, the AOD of GF-1 inversion and the ground observation data are consistent, but the satellite inversion value (0.74) is slightly higher than the observed value (0.56).
In addition, the correlation coefficient between the value of satellite inversion and AERONET in Beijing, Hangzhou and Hong Kong is 0.71, 0.55 and 0.54 respectively. The root mean square error (RMSE) is 0.29, 0.18 and 0.25 respectively. These results suggest that the three regions are well correlated. As shown in Table 1, the average AOD value of GF-1 inversion in Beijing is 0.69, the MAX is 2.86, and the MIN is 0.10. Relatively speaking, the observation of AERONET is 0.60, 3.02 and 0.07 respectively. The difference is small. However, from the slope of the scatter plot (0.65) and the intercept (0.31) point of view, there was a clear high value under-valuation situation which may be affect from the fact that Beijing is vulnerable to the factor of non-vegetation and snowfall in winter and this leads to the MODIS surface reflectivity product error becomes large. And then, it brings a greater impact to the dark blue algorithm. The results of GF-1 inversion are close to observations of AERONET in Hangzhou, and the RMSE of this area is relatively small (0.18). The analysis indicates that the inversion error of Hangzhou is mainly related to the aerosol model hypothesis and the aerosol pattern of the continental in this paper is quite different from the Yangtze River Delta.

In addition, the match sample points in Hangzhou are less, only 20. In Hong Kong, there is a significant overestimation problem with a low GF-1 inversion value (0.76) which is close to twice the ground observation (0.4). This is mainly caused by the cloud identification error of GF-1. Relative to the Beijing-Tianjin-Hebei and the Yangtze River Delta region, the Pearl River Delta cloud distribution is more. While the only four band settings of GF-1 lead to cloud recognition accuracy is significantly lower than the multi-channel MODIS and other sensors. If the thin cloud mistaken for the aerosol, it will result in significant over-estimation of the inversion results. Generally speaking, because of AERONET published less site data, this paper failed to fully verify the GF-1 results. And thus, in the future, we will consider using field test methods to obtain more ground-based data, and further the applicability of GF-1 products to test.

5. Summaries

At present, remote sensing applications using MODIS data are relatively mature, but there is little research on AOD inversion and validation based on high-resolution satellite remote sensing data. Therefore, in this paper, we use the dark pixel algorithm and the dark blue algorithm to perform the aerosol optical thickness inversion of dense vegetation and urban bright target areas respectively. And based on these results, we selected the Beijing-Tianjin-Hebei, Yangtze River Delta and the Pearl River Delta as a typical application demonstration area, the annual average distribution of the inversion results are discussed to analyze the three regions of the distribution of pollution characteristics. By using the AERONET ground-based observation data to verify the GF-1 AOD, we concluded that the correlation coefficients in national, Beijing, Hangzhou and Hong Kong were 0.6, 0.71, 0.55 and 0.54. And these indicate that GF1 inversion results can reflect the true distribution of atmospheric pollution to a certain extent. The analysis manifests that the AOD inversion error of GF1 mainly comes from the factors such as cloud recognition, surface reflectivity library accuracy and aerosol model. Therefore, these three aspects are also the focus of future AOD improvement based on high-resolution satellite data inversion.

| Region      | Data     | N | AVG | MAX  | MIN  | Slope | Intercept | RMSE  | $R^2$ |
|-------------|----------|---|-----|------|------|-------|-----------|-------|------|
| National    | GF-1     | 92 | 0.74| 2.86 | 0.10 | 0.64  | 0.38      | 0.28  | 0.6  |
|             | AERONET  |    | 0.56| 3.02 | 0.07 | 0.55  | 0.29      | 0.71  |      |
| Beijing     | GF-1     | 46 | 0.69| 2.86 | 0.10 | 0.65  | 0.31      | 0.29  | 0.71 |
|             | AERONET  |    | 0.60| 3.02 | 0.07 | 0.55  | 0.18      | 0.55  |      |
| Hangzhou    | GF-1     | 20 | 0.81| 1.21 | 0.42 | 0.74  | 0.31      | 0.18  | 0.55 |
|             | AERONET  |    | 0.68| 1.35 | 0.40 | 0.54  | 0.25      | 0.54  |      |
| Hong        | GF-1     | 26 | 0.76| 1.64 | 0.35 | 0.85  | 0.42      | 0.25  | 0.54 |
| Kong        | AERONET  |    | 0.40| 1.38 | 0.11 | 0.85  | 0.42      | 0.25  | 0.54 |

**Table 1.** Comparison results of GF-1 AOD and AERONET observation in China and three regions
6. Acknowledgments
This work was supported in part by National Natural Science Foundation of China under Grant 41571417. We thank the principal investigators (PI) and their staff for establishing and maintaining the AERONET sites used in this investigation. The work of Luo Zhang and Qiang Ge partially supported by the State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. We acknowledge the technical support of Shenshen Li.

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