Research on Aerosol Retrieval Algorithm of Multi-parameter Optimization Model

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Abstract. Aerosols can have an important impact on human society. Remote sensing method plays an important role in the aerosol retrieval. The aerosol retrieval SARA algorithm isn’t required a lot of prior knowledge and look-up table comparing with the traditional aerosol retrieval algorithms. However, the retrieval results of SARA algorithm are affected by the acquisition time differences and instability of MODIS data and AERONET data. In order to improve SARA algorithm, this paper studies the nonlinear optimization methods to construct the three-parameter model and the five-parameter model. And used the model to optimize the input parameters to improve the accuracy of aerosol retrieval. The correlation of five-parameter optimization results with AERONET sites Beijing and XiangHe is 0.7454 and 0.701 respectively, which is better than that of three-parameter optimization model’s 0.6012, 0.6479, and both are higher than SARA’s 0.3844 and 0.526.

1. Introduction
With the continuous improvement of the level of social and economic development and the continuous acceleration of infrastructure projects, the environmental pollution problems generated by various links have become increasingly prominent. According to the public information [1], 75.1% of the cities in the country exceeded air quality standard. As the political and cultural center and an important core area of the northern economy, the Beijing-Tianjin-Hebei region has an average of 43.2% of the days exceeding the air quality standard.

Aerosols can be defined as a relatively stable multiphase system composed of liquid or solid particles suspended in the atmosphere [2]. The scale ranges from nanometers to micrometers is uncertain, and existence time is also uncertain, it may exist weeks or hours. Aerosols will not only affect human production and life, but also adversely affect human health. More and more attention is paid to the monitoring and research of aerosols. Aerosol Optical Depth (AOD) is the most commonly used parameter to quantify aerosol. Traditional station monitoring method is suitable for small area, and limited to terrain condition. With the development of remote sensing technology, large-scale observation becomes possible, it can provide accurate information in time and provide an intuitive basis for ecological environment monitoring and governance. It has become one of the important monitoring methods for atmospheric research.
At present, there are many satellite remote sensing aerosols retrieval algorithms [3], such as dark pixel algorithms, deep blue algorithm, structure function algorithm. The above algorithms have their suitable areas, but most of them are suitable for urban areas and high reflectivity areas, some algorithms need more prior knowledges, such as aerosols type, look up table, the process is relatively complicated. A Simplified high-resolution MODIS (Moderate-resolution Imaging Spectroradiometer) Aerosols Retrieval Algorithm (SARA) was proposed in 2013 [4], compared with other aerosols retrieval algorithms, this algorithm does not need to establish a look-up table and enter the aerosols type in the retrieval area in advance, the results obtained have higher temporal and spatial resolution. It can directly use MODIS data products for retrieval, and uses MOD02HKM data, MOD03 data, and MOD09 data to obtain the value of apparent reflectance, geolocation and surface reflectance respectively. It is also necessary to use AERONET (AErosol RObotic NETwork) data as an auxiliary to obtain the values of SSA (Single Scattering Albedo) and ASY (Asymmetry Factor). However, the surface reflectance value obtained by MOD09 data cannot guarantee its accuracy. The data obtained through AERONET cannot be in good agreement with the time when the MODIS data is obtained due to the time difference.

In order to improve the accuracy of SARA retrieval, this paper uses nonlinear optimization methods to optimize the input parameters, and compares the SARA algorithm retrieval results and optimization results with the AOD values of ground-based observations.

2. Materials & Methods
This paper selects 23 days of MODIS data products from 2016 and the data from the AERONET of Beijing and Xianghe to perform AOD retrieval in the Beijing-Tianjin-Hebei region, some of the data used is slightly different in time. MODIS is an important sensor mounted on the Terra satellite. It has a wide range of bands and high time resolution. It has been widely used in resource surveys and atmospheric research.

The research area of this paper is shown in Figure 1. The main reasons for selecting Beijing-Tianjin-Hebei as the study area are: First, the data is sufficient, and AERONET site data can be obtained; Second, the Beijing-Tianjin-Hebei region is developing rapidly. With population growth and increased car ownership, air quality problems cannot be ignored [5].

![Figure 1](imageurl)
The spectral reflectance received by the top of the atmosphere (TOA) can be expressed by Equation (1):

\[
\rho_{\text{TOA}(\lambda, \theta_s, \theta_v, \phi)} = \rho_{\text{Aer}(\lambda, \theta_s, \theta_v, \phi)} + \rho_{\text{Ray}(\lambda, \theta_s, \theta_v, \phi)} + \frac{T_{(\theta_s)}T_{(\theta_v)}P_{s(\lambda, \theta_s, \theta_v, \phi)}}{1 - \rho_{s(\lambda, \theta_s, \theta_v, \phi)} S_{(\lambda)}}
\]

where \( \rho_{\text{TOA}(\lambda, \theta_s, \theta_v, \phi)} \) is satellite received TOA spectral reflectance, \( \lambda \) is wavelength in micrometers, \( \theta_s \) is solar zenith angle, \( \theta_v \) is view zenith angle, \( \phi \) is relative azimuth angle, \( \rho_{\text{Aer}(\lambda, \theta_s, \theta_v, \phi)} \) is aerosol reflectance, \( \rho_{\text{Ray}(\lambda, \theta_s, \theta_v, \phi)} \) is Rayleigh reflectance, \( T_{(\theta_s)} \) is transmission of the atmosphere on sun-surface path, \( T_{(\theta_v)} \) is transmission of the atmosphere on the surface-sensor path, \( \rho_{s(\lambda, \theta_s, \theta_v, \phi)} \) is surface reflectance, \( S_{(\lambda)} \) is atmospheric backscattering ratios. Equation (1) can be transformed into Equation (2), aerosol reflectance can be calculated by subtracting the Rayleigh path reflectance, and surface function from the satellite measured top of atmosphere reflectance:

\[
\rho_{\text{Aer}(\lambda, \theta_s, \theta_v, \phi)} = \rho_{\text{TOA}(\lambda, \theta_s, \theta_v, \phi)} - \rho_{\text{Ray}(\lambda, \theta_s, \theta_v, \phi)} - \frac{T_{(\theta_s)}T_{(\theta_v)}P_{s(\lambda, \theta_s, \theta_v, \phi)}}{1 - \rho_{s(\lambda, \theta_s, \theta_v, \phi)} S_{(\lambda)}}
\]

\( \rho_{\text{TOA}(\lambda, \theta_s, \theta_v, \phi)} \) can be obtained from MOD02 data, \( \rho_{\text{Ray}(\lambda, \theta_s, \theta_v, \phi)} \) can be calculated by Equation (3):

\[
\rho_{\text{Ray}(\lambda, \theta_s, \theta_v, \phi)} = \tau_{\text{Ray}} * P_{(\gamma(\theta))}
\]

where \( \tau_{\text{Ray}} \) is Rayleigh optical depth and \( P_{(\gamma(\theta))} \) is phase function, \( \tau_{\text{Ray}} \) can be calculated by Equation (4):

\[
\tau_{\text{Ray}} = \frac{P_\omega}{P_0} \left(0.00864 + 6.5 * 10^{-6} * z \right) \left(1 + 0.05 \right) \left(1.196 + 0.0074 * \lambda \right) \left(1 + 0.05 \right)
\]

where \( P_\omega \) ambient pressure with respect to elevation (mbar), \( P_0 \) is pressure at sea-level(mbar), \( z \) is ground elevation(km), \( P_{(\gamma(\theta))} \) can be calculated by Equation (5):

\[
P_{(\gamma(\theta))} = \frac{3}{4} (1 + \cos^2 \Theta)
\]

where \( \Theta \) is scattering angle and the value range is 0-180 degrees. The reflectance contributed by the ground surface is corrected with \( S_{(\lambda)} \), it can be expressed by Equation (6):

\[
S_{(\lambda)} = (0.92 * \tau_{\text{Ray}} + (1 - g) * \tau_a) \exp[-(\tau_{\text{Ray}} + \tau_a)]
\]

where \( \tau_a \) is aerosol optical depth, \( T_{(\theta_s)} \) and \( T_{(\theta_v)} \) can be expressed by Equation (7) and Equation (8) respectively:

\[
T_{(\theta_s)} = \exp(-\frac{\tau_{\text{Ray}} + \tau_a}{\mu_s})
\]

\[
T_{(\theta_v)} = \exp(-\frac{\tau_{\text{Ray}} + \tau_a}{\mu_v})
\]

where \( \mu_s \) is cosine of solar zenith angle, \( \mu_v \) is cosine of solar view angle. In the single scattering process, the aerosol reflectance can be calculated from the aerosol optical depth, single scattering albedo \( \omega_0 \) and the aerosol phase function \( P_{a(\lambda, \theta_s, \theta_v, \phi)} \), as Equation (9):

\[
\rho_{\text{Aer}(\lambda, \theta_s, \theta_v, \phi)} = \frac{\omega_0 \tau_{a(\lambda)} P_{a(\lambda, \theta_s, \theta_v, \phi)}}{4 \mu_s \mu_v}
\]
And the aerosol phase function can be calculated by Equation (10):
\[
P_{\theta_0}(\theta_v, \phi_0) = \frac{1 - g^2}{4\pi[(1 + g^2 - 2g\cos(\pi - \Theta))]^{1/2}}
\]
where \(g\) is asymmetry factor. Combine the above equations to get an equation (11) about \(\tau_a\):
\[
\tau_{a} = \frac{4\mu_{a,\lambda}}{\omega_{0}^{2}} \int P_{a}(\lambda_{0}, \theta_{a}, \phi_{a}) \cdot \frac{e^{-\tau_{\text{Ray}}(\lambda_{a})}}{\mu_{a}} \cdot \frac{e^{\tau_{\text{Ray}}(\lambda_{s})}}{\mu_{s}} \cdot P_{s}(\lambda_{0}, \theta_{s}, \phi_{s}) - \tau_{a} \cdot \exp[-(\tau_{\text{Ray}} + \tau_{a})] \ d\lambda_{0}
\]
Based on the result of SARA retrieval, an optimization model is introduced in the retrieval process and the input parameters are optimized using nonlinear optimization methods. Since the surface reflectance has a great influence on the results, a linear formula is used for fitting, as Equation (12):
\[
\rho'_{s}(\lambda_{s}, \theta_{s}, \phi_{s}) = k \cdot \rho_{s}(\lambda_{s}, \theta_{s}, \phi_{s}) + b
\]
where \(\rho'_{s}(\lambda_{s}, \theta_{s}, \phi_{s})\) is surface reflectance after fitting, \(k\) and \(b\) are custom parameters.

According to the number of optimized parameters, it can be divided into three-parameter optimization model and five-parameter optimization model. Three-parameter optimization model include AOD that from SARA retrieval, \(k\) and \(b\). Compared with the three-parameter optimization model, the five-parameter optimization model adds \(\omega_{0}\) and \(g\) from AERONET sites. We can use optimization tools to obtain optimization results, including objective function construction, boundary constraints, nonlinear constraints and output results. The technical flow chart of this paper is shown in Figure 2.

3. Results & Discussion
In order to ensure the accuracy of retrieval, images to be inverted should be cloudless or less clouded as much as possible. In this paper, according to the image quality and the effective monitoring data of the site, this paper selects the 23-day experimental data of Beijing Station and Xianghe Station. Due to the need for boundary constraints and initial value determination during optimization, the values of SSA and ASY of the two stations were counted. As we can see from Figure 3 that the trend of SSA and ASY are similar. In summer and autumn, it is slightly higher than that in winter and spring. The value of ASY...
changes relatively smoothly. According to this statistical value, the thresholds of both can be determined during optimization.

We compared the results of ground-based AOD with the results of SARA(a), three-parameter optimization model(b), and the five-parameter optimization model(c) respectively. The results are shown in Figures 4 and Figures 5. Figure 4 is the accuracy comparison of Beijing site, and Figure 5 is the accuracy comparison of Xianghe site. We can see from Figure 4 that the correlation between SARA retrieval results and ground-based monitoring values is 0.3844, after three-parameter optimization, the correlation is 0.6012, after five-parameter optimization, the correlation is 0.7454, and the retrieval accuracy is relatively improved. According to Figure 5, the correlation between the SARA retrieval result and the ground-based monitoring value is 0.526, the correlation after the three-parameter optimization is 0.6479, and the correlation after the five-parameter optimization is 0.701, and the retrieval accuracy is relatively improved. It can be seen from the overall trend that the accuracy of the retrieval result added with the optimized model is better than the SARA retrieval result. The accuracy of the five-parameter optimization model is higher than that of the three-parameter optimization model. When the AOD is low (<0.1), the accuracy of the SARA algorithm and the optimization model are relatively low, and there is obvious overestimation, even if the optimization algorithm is somewhat different improve. When the AOD value is higher (>0.6), the retrieval error increases. In general, the optimization effect of smaller values is better than larger values. Although there are errors in the results of nonlinear optimization, the accuracy is obviously better than that of SARA. For a better comparison, this paper compared the five-parameter retrieval results with MOD04 aerosol products, using data from November 8, 2016. The results are shown in Figure 6, (a) is MOD02 image, (b) is MOD04 image, (c) is SARA retrieval result image, (d) is the optimized result image. Overall, the optimized result is closer to the change trend of MOD04, as shown in the red box in the figure.
4. Conclusions

In this paper, in order to reduce the retrieval error caused by data time difference and instability in SARA retrieval, we used nonlinear optimization methods, the input parameters are optimized through the three-parameter model and the five-parameter model. The accuracy of the retrieval results was verified by using the monitoring data of Beijing and XiangHe sites in 2016. It was found that the results of five-parameter optimization model are better than the results of three-parameter optimization model, has a higher correlation with Beijing and XiangHe sites, both results are better than those of SARA.

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