

An inversion algorithm for simultaneous determination of vegetation reflectance and aerosol optical depth using satellite radiance data

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Abstract

Based on the property of vegetation reflectance spectra in the range from near-ultraviolet to near-infrared and the sensitivity of outgoing radiance to the reflectance and aerosol optical depth, a so-called iteration-correlation inversion algorithm is proposed to simultaneously derive the reflectance and aerosol optical depth. According to numerical inversion simulations, effects of the measurement error in radiance, the error in aerosol imaginary index and the vegetation ununiform on inversion results are analyzed. As shown in inversion simulations, as the error in the imaginary index is within 0.01, standard deviations of solutions of the reflectance and the optical depth for 14 wavelength channels are less than 0.063 and 0.023, and under 2% error of radiance, they are less than 0.023 and 0.0056, respectively, showing a satisfactory accuracy.

I. INTRODUCTION

Atmospheric aerosol optical depth and vegetation reflectance spectra properties are important to research environment and climate change, space-to-earth remote sensing and so on. Vegetation reflectance spectra properties can indicate vegetation growing status and season changes and affects the earth radiation budget, it is also one of the theoretical bases of space-to-earth remote sensing application, and it has been widely used in remote sensing information spotting, environment pollution monitoring, plant diseases and insect pests monitoring, crop yield estimating and geological minerals locating^[1-3]. Atmospheric aerosol optical depth is an important parameter characterizing atmospheric turbidity and a crucial factor determining aerosol radiance-climate effect. Spaceborne remote sensing is the sole means to determine aerosol optical depth and earth surface reflectance in the global scale. In the recent 20 years, research in spaceborne remote sensing of aerosol optical depth and earth surface reflectance has made important progress. Now there are two main methods for spaceborne remote sensing of aerosol optical depth. One is occultation method in which stratospheric optical depth is determined by measuring the solar direct radiation at sunrise and sunset with radiometer. The other is to retrieve atmospheric column aerosol optical depth from outgoing radiance information measured in space, which is mainly applied under the situation of ocean underlying surface^[4-5]. In the case of land surface, its reflectance is very complicated, and it is generally bigger than that of ocean, and so it has stronger effect on upward sky radiance. Therefore, spaceborne remote sensing of continent aerosol optical depth remains a question unresolved. Based on the vegetation reflectance properties from near ultra-violet to near infrared and the extraterrestrial radiance sensitivity to vegetation reflectance and atmospheric aerosol optical depth, a method for spaceborne remote sensing of the reflectance and the optical depth is proposed in this paper, and the corresponding iteration-correlation inversion algorithm is developed.

2. ANALYSIS OF SENSITIVITY

(1) Characteristics of vegetation reflectance

Whether surface reflectance and aerosol optical depth can be simultaneously retrieved from upward radiance information is crucially dependent on surface reflectance spectra characteristics. The bigger the surface reflectance is, the more it affects the radiance, and the more unfavorable it is to extract the optical depth out of the radiance, but the more favorable it is to retrieve surface reflectance.

Fig.1 shows average value, standard error, maximum and minimum of fifty sorts of the vegetation reflectance spectra from 410nm to 1000nm in Tong's book^[3]. In the 50 sorts of vegetation, 18 sorts are rice or wheat, 26 are different trees, and the rest is grassland or reed. Fig.2 shows 12 sorts of the vegetation reflectance spectra in the range of 410-1000nm. The 12 sorts of vegetation are rice, wheat, cotton, rape, sweet potato, astragalus sinicus, Chinese pine, Spruce, cypress, cedar, white poplar and grassland, respectively.

According to Figs.1-2, some characteristics of vegetation reflectance can be seen as follows:

(a) In the wavelength range of 410-500nm, reflectance is relatively smaller, being 2-65 times smaller than near infrared reflectance. Some of them is even smaller than sea water reflectance. The average of fifty sorts of

vegetation reflectance is less than 0.05, their standard deviation is less than 0.02, and the reflectance change comparatively little from 0.008 to 0.101.

(b) There are maximums of the reflectance in 550-560nm, which change within 0.05-0.3, and minimums of the reflectance can be found around 680nm.

(c) From 680 to 740nm, the reflectance increases obviously when the wavelength increases, and when it is bigger than 740nm in near infrared, the reflectance is usually very high. The average of fifty sorts of reflectance is larger than 0.38, the standard deviation is larger than 0.2, and the reflectance changes in the range of 0.19-0.84. The features above are identical with the research conclusions by Kontratyev (1969). The method of synthetic remote sensing for surface reflectance and aerosol optical depth proposed in this paper is just based on these features of vegetation reflectance.

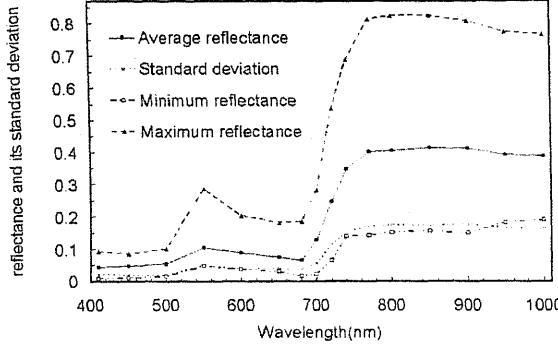


Fig.1 Average values, maximums, minimums and standard deviations of 50 sorts of vegetation reflectance

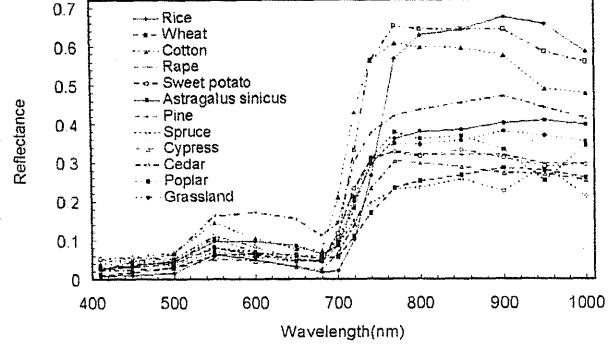


Fig.2 Twelve sorts of vegetation reflectance spectra

(2) Sensitivity of sky radiance to surface reflectance and aerosol optical depth

In this paper, Guass-Seidel iteration algorithm presented is adopted to solve radiation transfer equation, $I(\tau, \mu, \phi)$ stands for radiance. τ_a is aerosol optical depth. μ is cosine of zenith angle, ϕ is azimuth angle, μ_0 is cosine of solar zenith angle.

As discussed above, the vegetation reflectance in the wavelength less than 680nm and near infrared has different properties, so sensitivity of upward radiance at the representative wavelengths of 500nm and 800nm to surface reflectance and aerosol optical depth is emphatically analyzed in Fig.3 and Fig.4.

Fig.3 illustrates change of upward radiance at 500nm and 800nm with reflectance. In the figure, radiance is unity when surface reflectance is zero, meaning the radiance is relative. Here aerosol size distribution is Deirmendjian (1969) continental model^[6], and aerosol refractive index is 1.5-0.01i. It can be seen from Fig.3 that:

(a) The radiance increases when the reflectance increases.

(b) The radiance is very sensitive to the change of the reflectance, especially at the 800nm wavelength.

Under the condition that $\mu_0=1.0$, $\mu=1.0$, $\phi=0^\circ$ and $\tau_a=0.2$, when vegetation reflectance changes between 0 and 0.8, the radiation at 500nm and 800nm increases respectively 12 and 36 times. Additionally, because the vegetation reflectance in the wavelength less than 500nm is ordinarily less than 0.1, while the near infrared reflectance can change in a wide range of 0.18 to 0.85. So, the radiance channel in the wavelength less than 500nm is rather less sensitive to vegetation reflectance than near infrared channel, and it is favorable to retrieve aerosol optical depth.

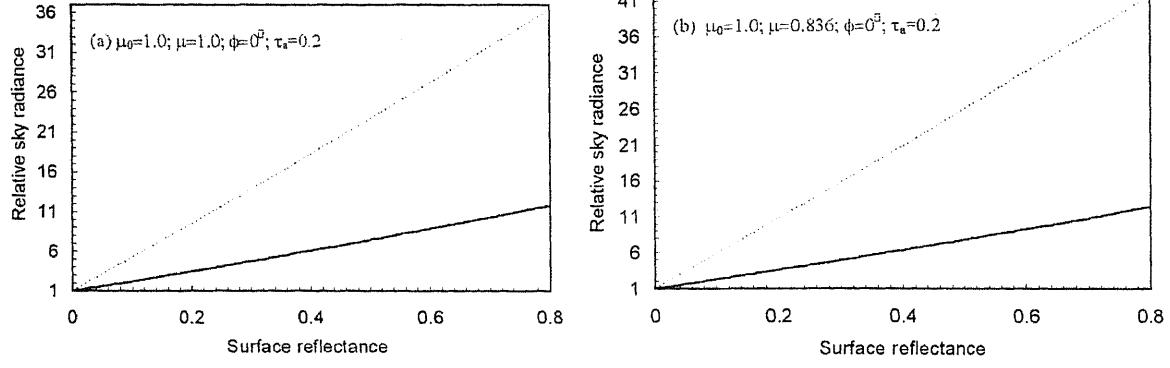


Fig.3 Sky radiance verse surface reflectance. Solid line: $\lambda=500\text{nm}$; dash line: $\lambda=800\text{nm}$

Fig.4 shows change of the upward radiation at 500nm and 800nm with aerosol optical depth. Here the radiance is set as 1 when the optical depth is zero, the reflectance for two wavelengths of 500nm and 800nm are average values of fifty sorts of vegetation reflectance as shown in Fig.2, being respectively 0.051 and 0.405. Aerosol size distribution is continental Diemendjian distribution, and aerosol complex refractive index is 1.5-0.01i. It can be seen from Fig.4:

- (a) The 500nm radiance is more sensitive to the aerosol optical depth than the 800nm radiance.
- (b) Sky radiance is more sensitive to the surface reflectance than the aerosol optical depth.

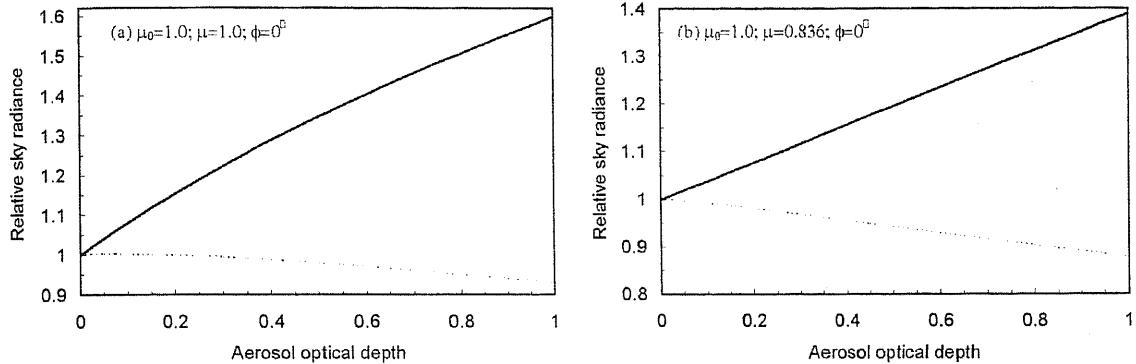


Fig.4 Sky radiance verse aerosol optical depth. Solid line: $\lambda=500\text{nm}$; dash line: $\lambda=800\text{nm}$

Because the upward radiance is more sensitive to surface reflectance than the aerosol optical depth, how to get the depth is the key of synthetic remote sensing. In brief, in the channels near the wavelength of 680nm and less than 500nm, vegetation reflectance is small, and for some channel it may even be less than sea water reflectance. Thus, these radiance channels have relatively weaker sensitivity to vegetation reflectance. Generally, it is more sensitive to aerosol optic depth than near infrared radiance. Furthermore, the change of vegetation reflectance in the wavelength less than 680nm (especially less than 500nm) is small. Hence, these channels are applicable to retrieve atmospheric aerosol optical depth by spaceborne remote sensing. Therefore, it is feasible to get the aerosol optical depth from upward radiance in the spectral channels of near 680nm and less than 500nm. Once aerosol optical depth is known, it can be used to improve vegetation reflectance retrieval.

III. RETRIEVAL ALGORITHM

According to the above sensitivity analyses, in the case of vegetation cover, there are two kinds of channel selections suitable for the inversion of aerosol optical depth. one is to choose two or more channels in the wavelength range of 400nm to 500nm, and another is to select several channels in the range of 400nm to 500nm plus the 680nm channel. The advantage of the first choice is that the change of vegetation reflectance of the channels between 400nm and 500nm is small. But by the consideration of sensitivity, the second choice is better. In the following numerical experiments, we used the second choice and selected three channels of 450nm, 500nm and 680nm, marked as λ_{a1} , λ_{a2} and λ_{a3} . Because upward radiance is more sensitive to surface reflectance than aerosol optical depth, it is very important to find an appropriate method to determine reflectance of the three wavelengths. In this paper, an iteration-correlation retrieval algorithm is proposed. In the algorithm, optimum reflectance solution of the three wavelengths is obtained by process of iteration and analysis the relationship between the reflectance solution and all the specimens in the reflectance library. The inversion steps goes like this:

(1) According to known information of surface reflectance measured, build a reflectance library covering a lot of vegetation kinds, in which the reflectance samples are marked as $A(j, \lambda_j)$, $j=1, \dots, N$, $i=1, \dots, M$. Here N is the total number of samples. λ_j is wavelength, M represents the total number of spectral channels.

(2) Assume Junge aerosol size distribution in inversion given by: $n(r) = cr^{-(v+1)}$,

Under the assumption of Junge distribution, aerosol optical depth can be written as:

$$\tau_a(\lambda) = \tau_a(\lambda_0 = 500\text{nm}) (\lambda_0 / \lambda)^{2-v}, \quad (7)$$

(3) Suppose that v_0 is the initial value of v , τ_0 is the initial value of $\tau_a(\lambda_0=500\text{nm})$, and the refractive index

of aerosol is known, then compute aerosol scattering phase functions and optical depths for M channels.

(4) Use the computed aerosol scattering phase functions and optical depths to search reflectance solutions for M channels by solving radiation transfer equation, written as $A_s(\lambda_i)$.

(5) Compute the correlation coefficient between $A_s(\lambda_i)$ and all the samples in the reflectance library as follows:

$$C_f(j) = \frac{f_{xy}}{\sqrt{f_x f_y}}, \quad (8)$$

where: $f_x = \sum_{i=1}^M [A_s(\lambda_i) - X]^2$, (8a)

$$X = \frac{1}{M} \sum_{i=1}^M A_s(\lambda_i), \quad (8b)$$

$$f_y = \sum_{i=1}^M [A_s(\lambda_i) - Y]^2, \quad (8c)$$

$$Y = \frac{1}{M} \sum_{i=1}^M A(j, \lambda_i), \quad (8d)$$

$$f_x = \sum_{i=1}^M [A_s(\lambda_i) - X][A(j, \lambda_i) - Y], \quad (8e)$$

(6) If reflectance specimen $j=k$ makes $C_f(j)$ the largest, corresponding with the best correlation to reflectance solution, then the reflectance of the three wavelengths λ_{a1} , λ_{a2} and λ_{a3} , corresponding to this specimen, are taken as their solution, written as A_{s1} , A_{s2} and A_{s3} , respectively.

(7) By solving radiation transfer equation, and using A_{s1} , A_{s2} and A_{s3} , to compute the solution of λ_{a1} , λ_{a2} and λ_{a3} aerosol optical depths, written as τ_{a1} , τ_{a2} and τ_{a3} , respectively.

(8) Using τ_{a1} , τ_{a2} and τ_{a3} , by the least square regression algorithm, to fit a Junge parameter v^* , written as v_s .

(9) Using v_s , compute aerosol scattering phase function, and according to equation (6) determine the optical depths of M channels except λ_{a1} , λ_{a2} , and λ_{a3} , again. Repeat steps (3) to (8). When the difference of optical depths between two iteration processes is less than a given value ϵ , iteration is ended.

5. NUMERICAL EXPERIMENTS

The iteration-correlation retrieval algorithm requires to build a vegetation reflectance library. In this paper, the library has 90 specimens, all gotten from the Ref.[3]. The twelve vegetation reflectance spectra in Fig.2 are chosen as true spectra in numerical experiments. Define the standard errors of aerosol optical depth and vegetation reflectance solutions in the twelve sets of numerical experiments using these reflectance spectra as:

$$\delta_a(\lambda_i) = \sqrt{\frac{1}{12} \sum_{j=1}^{12} [\tau_a(j, \lambda_i) - \tau_a^*(\lambda_i)]^2}. \quad (9)$$

$$\delta_s(\lambda_i) = \sqrt{\frac{1}{12} \sum_{j=1}^{12} [A(j, \lambda_i) - A^*(j, \lambda_i)]^2}. \quad (10)$$

where j is the ordinal number of the twelve kinds of vegetation. $\tau_a^*(\lambda_i)$ and $A^*(j, \lambda_i)$ is the true aerosol optical depth and vegetation reflectance for wavelength λ_i . $\tau_a(j, \lambda_i)$ and $A(j, \lambda_i)$ are their solutions, respectively. There are fourteen inversion channels, i.e. 410, 450, 500, 550, 600, 650, 680, 700, 720, 740, 770, 800, 850 and 900nm, among which the three channels of 450nm, 500nm and 680nm are used to retrieve aerosol optical depth. In inversion, the real part of the complex refractive index is supposed to be 1.5, the imaginary part is zero, and the initial value of optical depth is zero.

The following is to analyze the standard errors $\delta_a(\lambda_i)$ and $\delta_s(\lambda_i)$ in optical depth and reflectance solutions of the fourteen channels, according to Figs.5-6, where true aerosol size distribution is Junge distribution of $v^*=3$. The aerosol complex index of 1.5-0i, two values of $\tau_a(\lambda=500\text{nm})$ being 0.1 and 0.5 are selected.

As shown in From Figs.5-6, for all the wavelengths, standard errors of aerosol depth solutions are <0.026.

standard errors of reflectance solutions are <0.03. Inversion results are quite satisfactory. Under the condition of $\mu_0=1.0$ and $\mu=1.0$, in the range of 500nm to 800nm, the larger the wavelength, the less the standard errors of optical depth and reflectance solutions. But to the other three conditions, the larger the wavelength, the larger the standard errors.

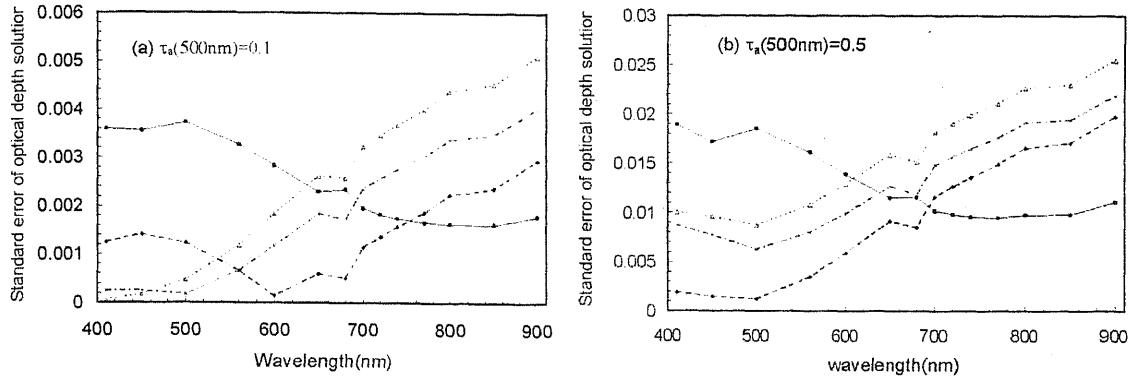


Fig.6 Standard error of aerosol optical depth solution under the Junge size distribution. •: $\mu_0=1.0, \mu=1.0$; ♦: $\mu_0=1.0, \mu=0.836$; Δ: $\mu_0=0.5, \mu=1.0$; ×: $\mu_0=0.5, \mu=0.836$.

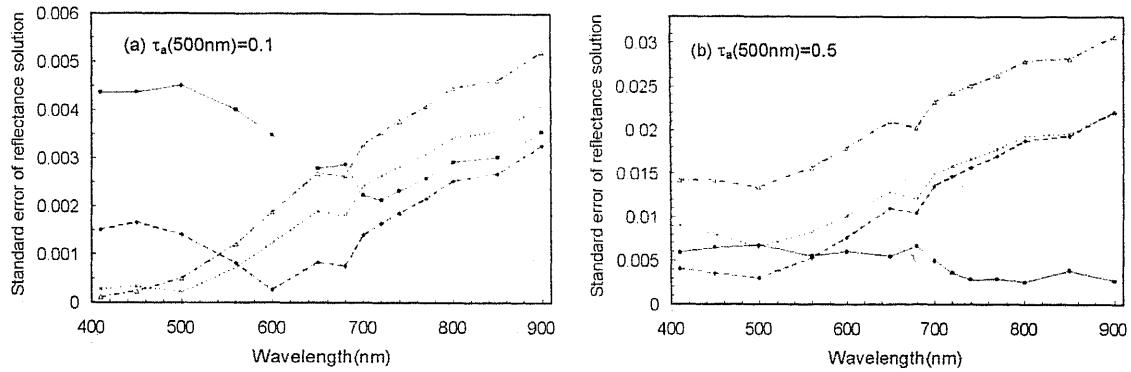


Fig.7 Standard error of vegetation reflectance solution under the Junge size distribution. •: $\mu_0=1.0, \mu=1.0$; ♦: $\mu_0=1.0, \mu=0.836$; Δ: $\mu_0=0.5, \mu=1.0$; ×: $\mu_0=0.5, \mu=0.836$.

Next, the effect of error in the aerosol imaginary index to optical depth and reflectance solutions is analyzed according to Table 2. Here σ_a and σ_s are standard errors of optical depth and reflectance solutions for fourteen channels, given by:

$$\sigma_a = \sqrt{\frac{1}{14} \sum_{i=1}^{14} [\tau_a(\lambda_i) - \tau_a^*(\lambda_i)]^2}. \quad (15)$$

$$\sigma_s = \sqrt{\frac{1}{14} \sum_{i=1}^{14} [A(\lambda_i) - A^*(\lambda_i)]^2}. \quad (16)$$

In Table 2, κ is true aerosol imaginary index, and v_S is solution of Junge parameter v^* , fitted from aerosol optical depth solutions for three wavelengths of 450nm, 500nm and 680nm. The true vegetation reflectance spectrum is a rice reflectance spectrum, the true aerosol distribution is Junge distribution of $v^*=3$, and the aerosol real index is 1.5. In inversion, the aerosol imaginary index is supposed to be zero. As shown in Table 1, as the imaginary index is larger, errors of aerosol optical depth, its size distribution and vegetation reflectance solutions are all larger. The larger the depth is, the distinct the error effect. In the condition of the imaginary index within 0.01, the solutions are idealistic. For example, when $\tau_a(\lambda=500\text{nm})=0.1$ and $\kappa=0.01$, σ_a , σ_s and v_S is 0.0157, 0.0035 and 2.6, respectively, errors being small. But when κ is equal to 0.05, σ_a , σ_s and v_S is 0.0312, 0.0136 and 2.3, respectively. The errors are larger obviously. In the case of $\tau_a(\lambda=500\text{nm})=0.5$, as $\kappa=0.0$, σ_a , σ_s and v_S is 0.0141, 0.0026 and 2.95, respectively, implying good precision; as $\kappa=0.01$, σ_a and σ_s is 0.079 and 0.0223, respectively, the solutions being reasonable; but as $\kappa=0.05$, σ_a and σ_s is 0.222 and 0.0721, respectively,

the errors being much larger.

Table 1 Effect of Error in Aerosol Imaginary Index on Optical Depth and Reflectance Solution. $\mu_0=0.5$, $\mu=1.0$.

$\tau_a(500\text{nm})$	0.1	0.1	0.5	0.5	0.5
k	0.01	0.05	0	0.01	0.05
σ_a	0.0157	0.0312	0.0141	0.0619	0.2215
σ_s	0.0035	0.0136	0.0026	0.0223	0.0721
v_s	2.6	2.3	2.95	2.4	2.0

In the case of spaceborne remote sensing, it is possible that vegetation sort in the field of view can be not single. Thus, the following analyses the inversion results under the condition of mixed vegetation spectrum reflectance from Table 2. Here the right reflectance spectrum is mixed of two rice reflectance spectra by the ratio of 7 to 3, the true aerosol complex index is $1.5-0.0i$. J_3 represents Junge distribution of $v=3$, DL represents continental Deirmenjian distribution^[6]. $\mu_0=0.5$ and $\mu=1.0$. As shown in Table 3, when $\tau_a(\lambda=500\text{nm})=0.1$, the standard errors of aerosol optical depth and surface reflectance are ≤ 0.0096 and 0.00333 for J_3 and DL distributions, and when $\tau_a(\lambda=500\text{nm})=0.5$, they are ≤ 0.0516 and 0.00677 , respectively. both of them have fairly good precision.

Table 2 Standard errors of optical depth reflectance solutions in the condition of a mixed surface.

	σ_a		σ_s	
J_3	0.0096	0.0243	0.00224	0.00677
DL	0.0061	0.0516	0.00333	0.00418
$\tau_a(\lambda=500\text{nm})$	0.1	0.5	0.1	0.5

Next, effect of the radiance error on inversion results is analyzed from Table 3. Here true wheat reflectance spectrum (as shown in Fig.2), and Junge distribution of $v=3$ are taken. $\mu_0=0.5$ and $\mu=1.0$. As shown in Table 3, in the case of 2% radiance error, when $\tau_a(\lambda=500\text{nm})=0.1$, the standard errors of aerosol optical depth and surface reflectance solutions are 0.0054 and 0.0032, and when $\tau_a(\lambda=500\text{nm})=0.5$, they are 0.0226 and 0.0056, respectively. The errors are small.

Table 4 Standard Errors of Optical Depth and Reflectance Solutions Caused by Radiance Error.

$\tau_a(\lambda=500\text{nm})$	σ_a	σ_r	σ_a	σ_r
0.1	0.0034	0.0016	0.0054	0.0032
0.5	0.0181	0.0068	0.0226	0.0056
Measurement error (%)	1			2

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