A parameterized SAILH model for LAI retrieval

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Abstract: The paper proposes a parameterized model based on the vegetation canopy radiative transfer model SAILH. This model simplifies the calculation of the nine intermediate variables of the SAILH model, and adapts an explicit formula to calculate the contribution of the single scattering in the illuminated canopy. We evaluate the retrieval accuracy and efficiency of the parameterized model with simulated data and ground-based measurements which are taken in the satellite-aircraft-ground synchronous experiment over the Heihe river basin in 2008.The results shows that the retrieval efficiency is improved greatly by the parameterized models but the retrieval accuracy is kept. It is also found that the stability of the parameterized model is better than the SAILH model.

Key words: SAILH model, parameterized, LAI retrieval

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1 INTRODUCTION

LAI (Leaf Area Index) is defined as sum of the one-side leaf area or half of the total leaf area per unit ground surface area (Chen, 1992). LAI is an important vegetation structural parameter, which is one of the basic parameters to characterize the canopy structure; it is related with many biological and physical processes of vegetation, such as photosynthesis, respiration, transpiration. Meanwhile it can also indicate the condition growth of the crops, so it is used commonly for crop yield estimation.

At present, the quantitative LAI retrieval methods using remote sensing are mainly classified as the empirical statistical model based method and the physical model inversion based method. The empirical statistical models use the vegetation index as the variable and retrieve LAI by establishing the statistical relationship between VIs and LAI (Fang & Zhang, 2003). This method dominates the LAI retrieval due to its simple expression and less parameters. Otherwise this method is lack of physical meaning, and the developed relationships between the VIs and LAI are dependent on the specific time and specific region. As a result, it is hard to expand its use in temporal and spatial dimensions. On the contrary, the physical models are more realistic and applicable. All the parameters of the models have physical meanings. There are some shortcomings in physical models, including too much parameters which are introduced into the models in order to describe the earth's surface features accurately as much as possible, and their expression are also very complicated.

Although the multi-spectral and multi-angle remote sensing technology provides more observational information, the remote sensing retrieval still faces the ill-posed problem, and the physical model retrieval is too slow to meet a wide range of application requirements. Therefore, it is important to find a parameterized model with certain physical meaning and simple form at the same time for the generation of large area LAI products. In this paper, we proposes a parameterized model based on the SAILH model, and then we compare the retrieval accuracy, efficiency and stability between the parameterized model and the SAILH model with simulated data and ground-based measurements which are taken in the Heihe river basin.

2 INTRODUCTION OF THE SAILH MODEL

Canopy reflectance models can be divided into three kinds of model in accordance with whether it is established according to the theoretical analysis, that is the empirical models, semi-empirical models and physical models (Zhao, 2007), while the physical models can be divided into radiative transfer models, geometric optics models, and computer simulation models. SAILH model is one kind of the radiative transfer models. The basis of the radiative transfer models is the radiative transfer equation, which is an integral - differential equa-

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tion. In theory, the equation is solvable if the boundary conditions are determined. So far, there is no rigorous analytical solution to the radiation transfer equation but only a variety of approximate solutions (Xu, 2006). The commonly used solution is the K-M equation proposed by Kubelka and Munk. The incident light is divided into four parts in the SAIL model (Scattering by Arbitrarily Inclined Leaves) (Verhoef, 1984) based on the K-M equation, that are the upward and downward radiation flux density as well as the upward and downward parallel radiation irradiation. By solving nine intermediate variables (including the extinction coefficient (*ks*) of the direct radiation flux density, attenuation coefficient (*att*), back-scattering coefficient (*sig*), forward and backward scattering coefficient of the direct radiation (*sf*, *sb*), conversion coefficients from upward, downward radiation flux density and upward parallel radiation to the observed radiance(*uf*, *ub*, ω), the extinction coefficient of the radiation flux density on the observed direction (*ko*)), the canopy reflectance can be got. So SAIL model is a four-stream linear differential equation with nine coefficients. Its input parameters include three structural parameters and four spectral parameters, where the three structural parameters are the leaf area index and the two parameters which are used to describe the leaf inclined angles. The four spectral parameters are the ratio of sky light, leaf reflectance, leaf transmittance and soil reflectance.

As the SAIL model can not simulate the hot-spot effect well, Kuusk added the hot-spot effect to the SAIL model and developed the SAILH model (Kuusk, 1991). Hotspot effect is caused by the single scattering of the illuminated canopy. Therefore, Kuusk established the relevant probability model between the direction of observation and the direction of the incident light to consider the canopy hot-spot effect based on the SAIL model. In SAILH model, the contribution of the single scattering of the whole canopy is decomposed into multi-layer single-scattering contribution and summed together as the contribution of the whole canopy. In the calculation of the single scattering contribution of each layer, a bi-directional transmission density function is used. The bi-directional transmission density function calculation needs to introduce a new parameter—the hot-spot effect factor. Then there are eight input parameters in SAILH model (See Table 1, the meanings of these parameters can be found in the appendix).

Table 1 Input parameters' settings of the SAILH model

LAI	θ_m	ε	s_L	skyl	ρ	τ	ρ_s
2	45°	0.1	0.1	0.10	0.08	0.08	0.10

3 ESTABLISHMENT OF THE PARAMETERIZED MODEL

In practical applications, remote sensing is the most effective technique which is able to get large-scale and time series LAI of different surface types. A large number of studies have shown that using remote sensing technology can extract regional and global LAI rapidly and periodically, and can provide spatial and temporal distribution of LAI (Hui *et al.*, 2003). Although SAILH model is a widely accepted model to describe the directional reflectance of continuous vegetation canopy, its practicality is limited due to its complicated calculation and low retrieval efficiency. So in order to improve the retrieval efficiency and keep the accuracy, it is necessary to make some reasonable simplifications to the model. We proposed a parameterized model based on SAILH model in this paper, and evaluated the retrieval accuracy, efficiency and stability of the parameterized model based on the simulated data and ground-based measured data.

This work aimed at the following two steps: (1) Simplifying the calculation of the nine intermediate variables of the SAILH model. (2) Simplifying the calculation the contribution of the single scattering of the illuminated canopy.

3.1 Simplification of the calculation of the nine intermediate variables of the SAILH Model

The main reason of the low retrieval efficiency of SAILH model is that when calculating the canopy reflectance, the leaf inclined angles of continuous canopy are divided into 13 angles and the nine intermediate variables are expressed as the functions of these leaf inclined angles, then the result is calculated by summing these 13 terms iteratively. If we can simplify the calculations of these nine intermediate variables and keep the rest calculations in SAILH model, we may improve the efficiency greatly. Through analyzing and comparing the calculation of the nine intermediate variables in SAILH model, we have the simplified calculations shown in Table 2, where, LAI is the leaf area index, $\mathrm{LAI}' = \frac{\mathrm{LAI}}{h}$, and *h* is the canopy height; θ_l is the leaf inclined angle, and $f(\theta_l)$ represents the leaf inclination density function; β_s and β_v are the critical angles of the light direction and the observed direction respectively, the calculation of these two variables can be found in Verhoef (1984); $G(\theta_i)(i=s, v)$ is the *G* function (subscript *s* represents the illumination direction, and *v* represents the observed direction, the same as follows), $\mu_i=\cos\theta_i(i=s, v)$, α is the angle between the light direction and the observed direction, and its calculation equation is:

$$\alpha = \cos^{-1}(\mu_s\mu_v + \sin\theta_s \sin\theta_v \cos(\varphi_s - \varphi_v)) \tag{1}$$

In the calculation of nine intermediate variables, the most complex one is ω, which indicates that if the illumination direction and the observed direction intersect at the same side of the leaf, the leaf reflectance should be used to represent the reflection of the leaf to the light, otherwise the leaf transmittance should be used to represent the weaken of the leaf to the light. In this sense, ω represents a similar concept with the scattering phase function, but the difference is that it contains LAI, so in the calculation later, we use the scattering phase function to

Table 2 The expressions of the nine intermediate variables in SAILH model and parameterized model

	SAILH model (Verhoef, 1984)	Parameterized, model
att	$\sum\left(\mathrm{LAI}'\times\left(1-\frac{\rho+\tau}{2}+\frac{\rho-\tau}{2}\times\cos^2\theta_1\times f(\theta_1)\right)\right)$	$\mathrm{LAI}\times\left(1-\frac{\rho+\tau}{2}+\frac{\rho-\tau}{2}\times\sum(\cos^2\theta_1\times f(\theta_1))\right)$
sig	$\sum\left(\mathrm{LAI}'\times\left(\frac{\rho+\tau}{2}+\frac{\rho-\tau}{2}\times\cos^2\theta_1\times f(\theta_1)\right)\right)$	$\mathrm{LAI}\times\left(\frac{\rho+\tau}{2}+\frac{\rho-\tau}{2}\times\sum(\cos^2\theta_1\times f(\theta_1))\right)$
sf	$\sum\left(\frac{\rho+\tau}{2}\times\mathrm{ks}(\theta_1)-\frac{\rho-\tau}{2}\times\mathrm{LAI}'\times\cos^2\theta_1\times f(\theta_1)\right)$	$\frac{\rho+\tau}{2}\times\frac{G(\theta_s)\times\mathrm{LAI}}{\mu_s}-\frac{\rho-\tau}{2}\times\mathrm{LAI}\times\sum(\cos^2\theta_1\times f(\theta_1))$
sb	$\sum\left(\frac{\rho+\tau}{2}\times\mathrm{ks}(\theta_1)+\frac{\rho-\tau}{2}\times\mathrm{LAI}'\times\cos^2\theta_1\times f(\theta_1)\right)$	$\frac{\rho+\tau}{2}\times\frac{G(\theta_s)\times\mathrm{LAI}}{\mu_s}+\frac{\rho-\tau}{2}\times\mathrm{LAI}\times\sum(\cos^2\theta_1\times f(\theta_1))$
ks	$\sum\left(\frac{2}{\pi}\times\mathrm{LAI}'\times\left[(\beta_s-\frac{\pi}{2})\cos\theta_1+\sin\beta_s\tan\theta_s\sin\theta_1\right]\times f(\theta_1)\right)$	$\frac{G(\theta_s)\times\mathrm{LAI}}{\mu_s}$
ko	$\sum\left(\frac{2}{\pi}\times\mathrm{LAI}'\times\left[\begin{array}{l}(\beta_v-\frac{\pi}{2})\cos\theta_1+\\ \sin\beta_v\tan\theta_v\sin\theta_1\end{array}\right]\times f(\theta_1)\right)$	$\frac{G(\theta_v)\times\mathrm{LAI}}{\mu_v}$
uf	$\sum\left(\frac{\rho+\tau}{2}\times\mathrm{ko}(\theta_1)-\frac{\rho-\tau}{2}\times\mathrm{LAI}'\times\cos^2\theta_1\times f(\theta_1)\right)$	$\frac{\rho+\tau}{2}\times\frac{G(\theta_v)\times\mathrm{LAI}}{\mu_v}-\frac{\rho-\tau}{2}\times\mathrm{LAI}\times\sum(\cos^2\theta_1\times f(\theta_1))$
ub	$\sum\left(\frac{\rho+\tau}{2}\times\mathrm{ko}(\theta_1)+\frac{\rho-\tau}{2}\times\mathrm{LAI}'\times\cos^2\theta_1\times f(\theta_1)\right)$	$\frac{\rho+\tau}{2}\times\frac{G(\theta_v)\times\mathrm{LAI}}{\mu_v}+\frac{\rho-\tau}{2}\times\mathrm{LAI}\times\sum(\cos^2\theta_1\times f(\theta_1))$
ω	seeverhoef(1984)	$\frac{\rho+\tau}{3\pi}\times(\sin\alpha-\alpha\times\cos\alpha)+\frac{\rho}{3}\times\cos\alpha$

approximate the calculation of $\frac{\omega}{\mathrm{LAI}}$ in SAILH model.

The two-parameter elliptic distribution is used to describe the leaf inclined angle distribution in SAILH model. In order to make a better approximation to the scattering phase function of this distribution, we choose the scattering phase function of spherical distribution to replace it. We can get a better approximation using this scattering phase function instead of $\frac{\omega}{\mathrm{LAI}}$ when $\varepsilon\leqslant 0.9$, but when leaf angle distributions are the extreme types, there will be a little bias to the results. When the leaf angle distribution is approximately perpendicular, the relative error introduced is 30%; and when the leaf angle distribution is approximately planar, the relative error introduced is 20%. Fig. 1 shows that when the input parameters were set as shown in Table 1, the comparison of the nine intermediate variables calculated by SAILH model and the parameterized model. In Fig.1, the sun zenith angle is set at 35°, the view zenith angle is from 0° to 60° with an increment of 10°, and the relative azimuth angle between the sun and the view is 0° which represented in the principle plane, and the positive values of the view zenith angles represents the backward observations. We can get from Fig. 1 that the results of the nine intermediate variables calculated by SAILH model and parameterized model are very close to each other without considering the extreme leaf inclined angle distribution case, and we get the same answers in both the red and near-infrared bands.

3.2 The calculation of the contribution of the single scattering of the illuminated canopy

Supposed that the continuous vegetation canopy is composed by a series of horizontal and uniform layers, then the contribution of single scattering of the illuminated canopy P_c^1 can be calculated as follows (Kuusk, 1991).

$$P_c^1=\frac{\Gamma(\Omega_s,\Omega_v)}{\mu_s\mu_v}\int_0^H u_L(z)P(z,\Omega_s,\Omega_v)\mathrm{d}z \tag{2}$$

where $\Gamma(\Omega_s,\Omega_v)$ is the scattering phase function, $u_L(z)$ is the leaf area density, and $P(z,\Omega_s,\Omega_v)$ is the bi-directional gap probability function and it can be calculated as follows.

$$P(z,\Omega_s,\Omega_v)=P_s(z)P_v(z)C_{HS}(z,\Omega_s,\Omega_v) \tag{3}$$

In Eq.(3), $P_s(z)$ and $P_v(z)$ are the average gap probability of the sunlight and view direction respectively, and $C_{HS}(z,\Omega_s,\Omega_v)$ is the hotspot factor and its calculation can be found in the article written by Kuusk (1991). When calculating Eq. (2) in SAILH model, it is assumed that the leaf area density $u_L(z)$ does not changed with canopy height and is put outside of the integration sign referred as a constant and participates in the calculation of the nine variables, and then only make integration to the bi-directional gap probability function $P(z,\Omega_s,\Omega_v)$. Since the integration can't get a clear analytical expression, so a simpson method is used in SAILH, that is, the whole canopy is divided into 20 layers, and then sums the results of these 20 layers as the result of integration. However, if make integration to $\int_0^H u_L(z)P(z,\Omega_s,\Omega_v)\mathrm{d}z$ directly, then we can get an analytical expression to calculate the single scattering of the illuminated canopy as follows.

$$P_c=\frac{1-P_g}{a_s+a_v-\sqrt{a_s a_v}\times\frac{\mathrm{s\_L}}{\Delta}\times(1-\exp(-\frac{\Delta}{\mathrm{s\_L}}))} \tag{4}$$

where P_g represents the proportion of the visible illuminated soil area, and can be calculated as follows through making integration to Eq.(3):

$$P_g=\exp(-(a_s+a_v-\sqrt{a_s a_v}\times\frac{\mathrm{s\_L}}{\Delta}\times(1-\exp(-\frac{\Delta}{\mathrm{s\_L}})))\times\mathrm{LAI}) \tag{5}$$

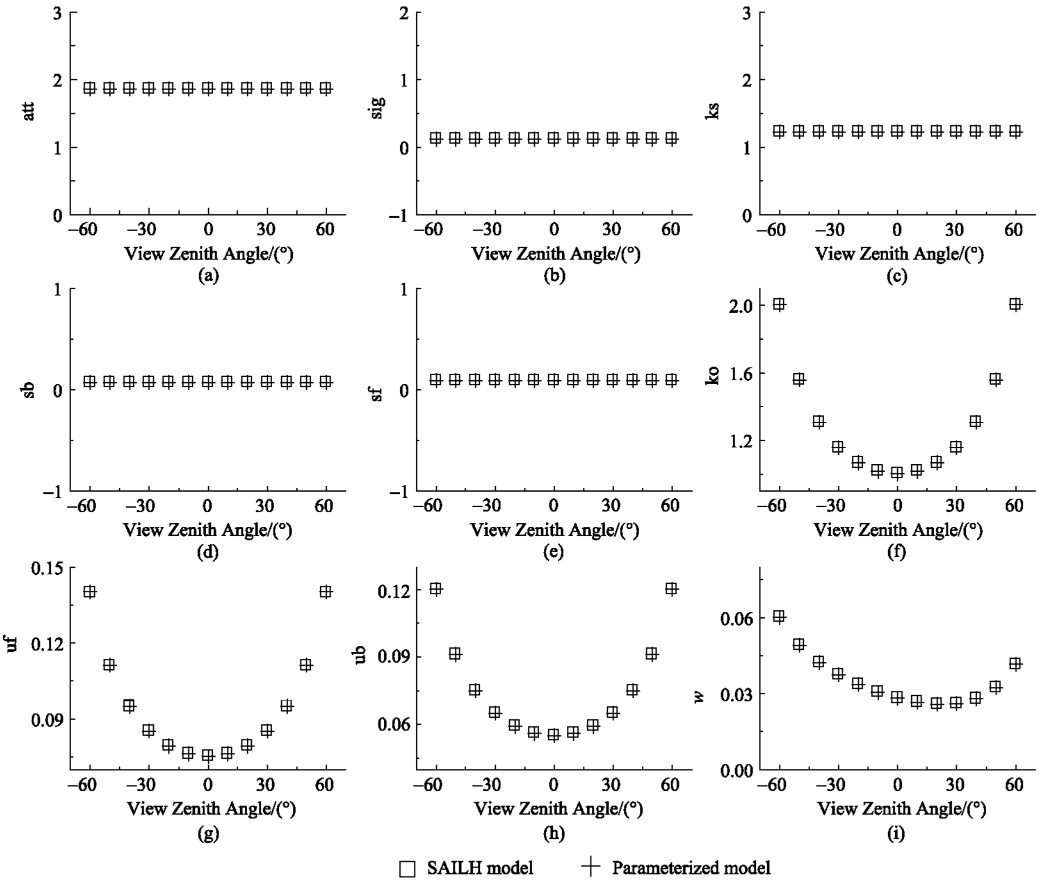

Fig. 1 Comparison of the calculation of nine intermediate variables in SAILH model and parameterized model
(a) att; (b) sig; (c) ks; (d) sb; (e) sf; (f) ko; (g) uf; (h) ub; (i) *w*

where:

$$a_i = \frac{G(\theta_i)}{\mu_i}(i = \mathrm{s,v}) \tag{6}$$

s_L is the hotspot factor parameter, the calculation of Δ is:

$$\Delta = \sqrt{\frac{1}{\mu_s^{2}} + \frac{1}{\mu_v^{2}} - \frac{2\cos\alpha}{\mu_s\mu_v}} \tag{7}$$

To test the correctness of the Eq. (4), we compared the result calculated by it with the result of the SAILH model (Fig. 2). P_c represents the result of Eq.(4) , the curve marked as 20 represents the result calculated by SAILH model when the canopy are divided into 20 layers; Similarly, the curves marked as 50 and 100 represent the results calculated by SAILH model when the canopy are divided into 50 and 100 layers respectively. It can be seen from Fig. 2 that, if the canopy are divided into more layers, the result calculated by SAILH model will be closer to the result calculated by the Eq.(4), as a result, the correctness of Eq.(4) is obvious.

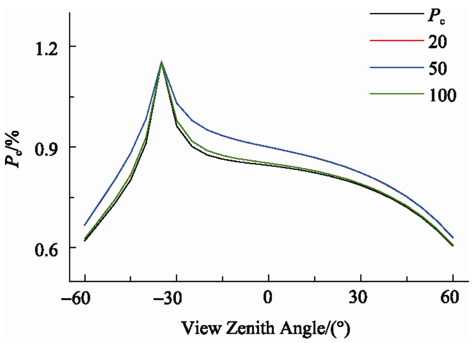

Fig. 2 The validity of the Eq. (4)

Then, the contribution of the single scattering of the illuminated canopy can be calculated as follows:

$$P_c^1 = \frac{\Gamma(\Omega_s, \Omega_v)}{\mu_s\mu_v} P_c \tag{8}$$

So far, the calculations of the nine intermediate variables and the contribution of single scattering of the illuminated canopy have been simplified, and the other calculations keep the same as SAILH model.

We designe a group of experiments to compare and evaluate the forward BRDF simulated ability of the parameterized model. We set the sun zenith angle at 35° and the solar azimuth angle at 0°, the observation zenith angles are changes from 0° to 85° with an increment of 5°, and the observation azimuth angles are from 0° to 355° with the same interval changes of 5°, so there are a total of 1296 observation combinations in the upward hemisphere. The values of the input structural parameters are shown in Table 3. We design the parameters for the following three considerations: (1) Group Ⅰ: the elliptical eccentricity is set at 0.001, in which case the leaf inclined angle distribution near to a spherical leaf angle distribution, the forward BRDF simulation ability of the parameterized model is evaluated when

LAI=2 and LAI=4, respectively; (2) Group Ⅱ: the elliptical eccentricity is set at 0.9, and the average leaf inclined angle is set at different values, when θ_m=0.001° the leaf inclined distribution is nearly to a planar distribution, when θ_m=89.9° the leaf inclined distribution is nearly to a perpendicular distribution, θ_m=35° and θ_m=65° represent two kinds of transition leaf inclined angle distributions and then compare the forward BRDF simulation ability when LAI=2; (3) Group III: the value of LAI is set at 4 and all the other parameters are kept as the same as Group Ⅱ. For the spectral parameters, we set the ratio of skylight, leaf reflectance, leaf transmittance and soil reflectance at 0.1,0.1,0.12 and 0.1 respectively in the red band, and the values are fixed at 0.1,0.45, 0.5 and 0.2 respectively in the near-infrared band.

Table 3 The input structural parameters when comparing the forward BRDF simulation ability

Group	Group Number	LAI	θ_m/(°)	ε	s_L
Group Ⅰ	1	2	45	0.001	0.1
	2	4	45	0.001	0.1
Group Ⅱ	3	2	0.001	0.9	0.1
	4	2	35	0.9	0.1
	5	2	65	0.9	0.1
	6	2	89.9	0.9	0.1
Group III	7	4	0.001	0.9	0.1
	8	4	35	0.9	0.1
	9	4	65	0.9	0.1
	10	4	89.9	0.9	0.1

The RMSEs and the correlation coefficients of the forward simulated BRDF of the entire upward hemisphere between the parameterized model and SAILH model are used as the evaluate criterion. The results are shown in Table 4. Through analysis we can see that, in the entire upward hemisphere, the RMSEs of the forward simulated BRDF between the parameterized model and SAILH model can be maintained below 0.01 in the red band, and below 0.04 in the near-infrared band; whether in red or near-infrared band, the correlation coefficients of the parameterized model and SAILH model has reached more than 96%.

Table 4 Fitting capacity assessment of the parameterized model

Group Number	Root mean square error (RMSE)		Correlation Coefficient	
	Red band	Near-Infrared band	Red band	Near-Infrared band
1	0.00341	0.01192	0.97911	0.99838
2	0.00554	0.02204	0.99075	0.99398
3	0.00475	0.02739	0.98855	0.99482
4	0.00443	0.02367	0.98751	0.99431
5	0.00280	0.00662	0.97596	0.99719
6	0.00253	0.01169	0.96194	0.99051
7	0.00784	0.03958	0.98945	0.97686
8	0.00727	0.03550	0.99119	0.97877
9	0.00441	0.01243	0.98723	0.99417
10	0.00374	0.01104	0.97549	0.98451

4 MODEL EVALUATION

There is a high positive correlation between the BRDF simulations between the parameterized model and SAILH model, so the SAILH model can be represented by the parameterized model to some degree. Then we evaluated the retrieval accuracy, efficiency and stability of these two models using simulated data and ground-based measured data.

4.1 Model Evaluation Based On Simulated Data

The generation of simulated data is as follows: supposing a group or several groups of input parameters, giving the appropriate prior knowledge, taking the SAILH forward simulated values as the observed true values, and then retrieving parameters using the parameterized model with Powell optimization algorithm. For the purpose of comparison, we also retrieved the LAI values used the SAILH model with the same prior knowledge at the same time. We added 10% Gaussian noise to the observed values during retrieval.

4.1.1 The comparison of the retrieval accuracy of the models

We use the absolute errors between the retrieved LAI values and the input LAI values in forward simulation as the evaluation criterion of the retrieval accuracy. Fig. 3 shows the relationship between the input LAI values and the retrieved LAI values, in which the X axis is for the input LAI values, and the Y axis for the retrieved LAI values. Fig. 4 indicates the relationship of the retrieval absolute error s' changes with the input LAI changes.

From Fig. 3 and Fig. 4 we can conclude that: there is no great degree loss of the retrieval accuracy for the parameterized model compared with SAILH model; from the absolute error

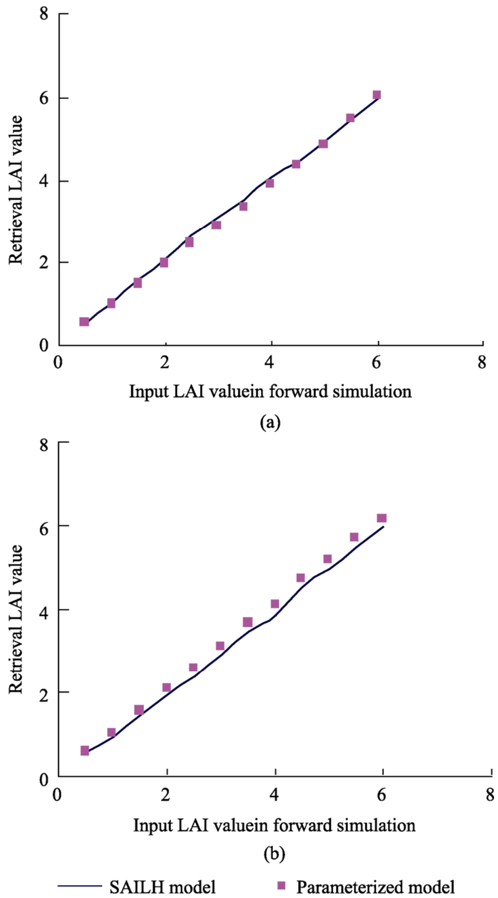

Fig. 3 The comparison between the retrieved LAI values and the input LAI values

(a) Red band; (b) Near-infrared band

terms, the maximum retrieval errors is 0.180 and 0.122 in red and near-infrared bands respectively for SAILH model, while the maximum retrieval errors was 0.179 and 0.197 in red and near-infrared bands respectively for the parameterized model.

4.1.2 The comparison of the efficiency of the model

The method we use to evaluate the retrieval efficiency of the parameterized model is as follows: using 6 observations of different angles in each retrievals, setting different retrieval times of 50 times, 100 times, 200 times and 500 times respectively, and then computing the running time. Each test is repeated for five times, and then take the averaged running time as the evaluation criterion of the retrieval efficiency. The results are shown in Fig. 5. What we can see from Fig. 5 is that, in the terms of retrieval efficiency, the retrieval efficiency is significantly improved by 10 times of the parameterized model compared with SAILH model.

4.1.3 The comparison of the stability of the model

For the stability evaluation of the model, we use the following methods: in the retrieval, we compared the retrieval accuracy of LAI by increasing the noise in the simulated data (choose the relative error as the evaluation criterion). The results are shown in Fig. 6. We can see from Fig. 6 that, the retrieval error is bigger as the noise increases, and the stability of the parameterized model is superior to SAILH model whether in the red band or the near-infrared band.

4.2 Model Evaluation Based On Ground Measurements

The parameterized model is evaluated by using the ground-based

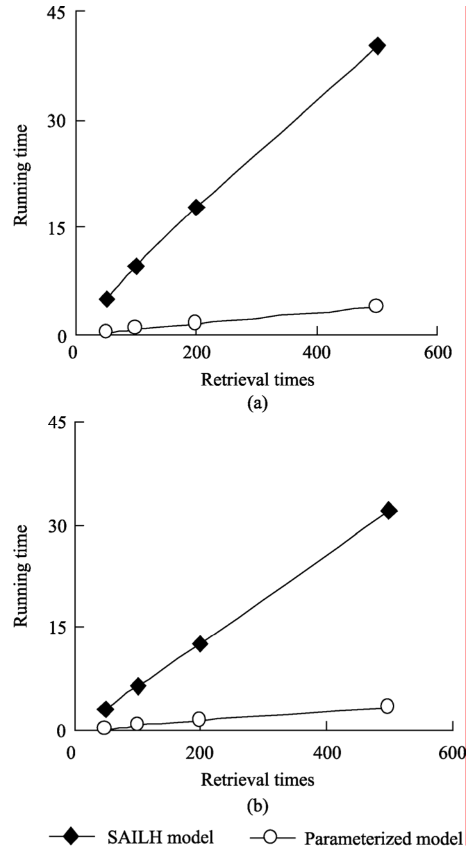

Fig. 5 The comparison of retrieval efficiency between SAILH model and parameterized model

(a) Red band; (b) Near-infrared band

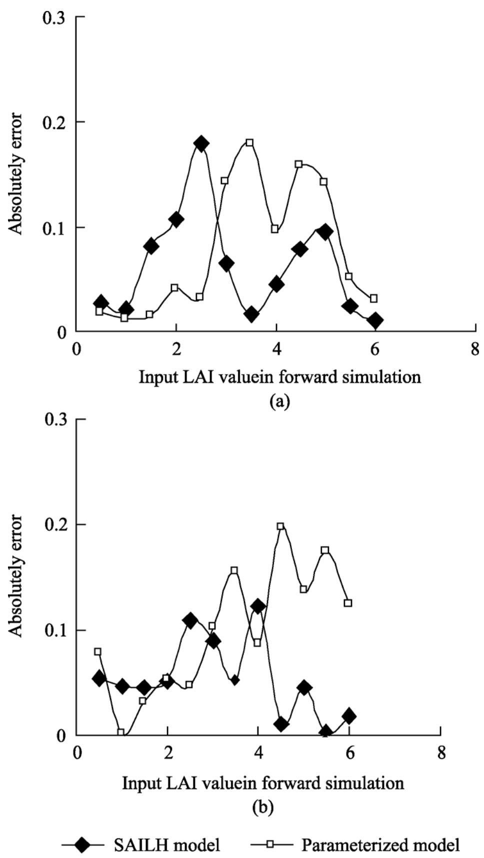

Fig. 4 The comparison of retrieval absolutely errors between SAILH and Paremeterized model

(a) Red band; (b) Near-infrared band

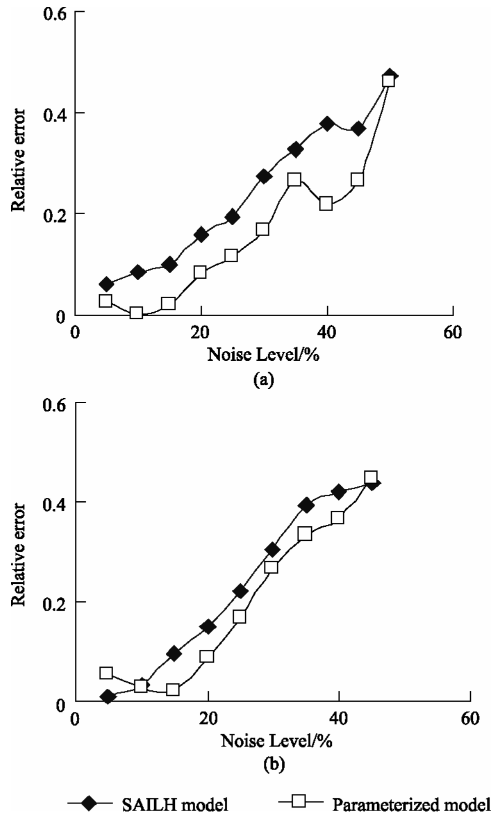

Fig. 6 The comparison of model stability of SAILH model and parameterized model

(a) Red band; (b) Near-infrared band

measured canopy reflectance data and LAI data in YingKe from the satellite-aircraft-ground synchronous experiment over the Heihe river basin in 2008. There were two measurement sets in June 22 and July 1 respectively and only one measurement set in July 9 in the experimental area. Thus, there were total 5 groups of measurement sets. We retrieved the eight input parameters meanwhile using the same Powell optimization algorithm. Among these input parameters, the expectations and uncertainties of LAI, leaf reflectance, leaf transmittance and soil reflectance were obtained by ground measurements; the expectations of the average leaf inclined angle and the elliptical eccentricity were retrieved from measured LAD data, and the uncertainties of these two parameters were set at 0.01; the expectations and uncertainties of the hot-spot effect factor parameter and the ratio of sky light were set at 0.1 and 0.01, respectively. The setting of the expectations and uncertainties of the input parameters are listed in detail in Table 5.

Table 5 The Setting of the input parameters and Priori knowledge

Input Parameters	Red band		Near-infrared band	
	Expectations	Uncertainty	Expectations	Uncertainty
LAI	3	0.4	3	0.4
θ_m	45°	0.01	45°	0.01
ε	0.6	0.01	0.6	0.01
s_L	0.1	0.01	0.1	0.01
skyl	0.1	0.01	0.1	0.01
ρ	0.08	0.01	0.45	0.03
τ	0.05	0.01	0.5	0.03
ρ_s	0.17	0.01	0.2	0.03

4.2.1 The comparison of the retrieval accuracies of the models

In the ground measurements except that taken on July 9 in Heihe field campaign, there were canopy reflectance data of four planes in each measurement including the solar principal plane, the vertical principal plane, the parallel row plane and the cross row plane respectively (measurements were only available at the solar principal plane and vertical principal plane on July 9). In our retrieval tests, first we use the measured data of each plane to retrieve respectively, and then use the data of all four planes together to retrieve LAI. At last, we get the results as follows: compared with the ground measured LAI data, the maximum retrieval absolute error is 1.344 of SAILH model, and the minimum absolute error is 0.002; the maximum retrieval absolute error is 0.807 of the parameterized model, and the minimum retrieval absolute error is 0.056. Thus, the retrieval error of the parameterized model is in an acceptable range.

4.2.2 The comparison of the efficiency of the model

We also evaluate the retrieval efficiency of the parame- terized model by using the measured data, and get the same conclusion that the retrieval efficiency is greatly improved for 8—10 times by the parameterized model.

5 CONCLUSION AND DISCUSSION

In this paper, we proposes a parameterized model based on SAILH model. In the new model, we simplify the calculation of the nine intermediate variables in SAILH model, and also simplify the calculation of the single scattering contribution of the illuminated canopy at the same time, and then keep the rest calculations the same with the SAILH model. We evaluates the retrieval accuracy, efficiency and stability of the parameterized model with simulated and measured data respectively, and then we get some conclusion as follows.

(1) In the entire upward hemisphere, there is a strong correlation between the simulated BRDF by the parameterized model and the SAILH model, the correlation coefficients reached more than 96% in both red and near-infrared band, and the RMSE in the red band can be maintained below 0.01, while in the near-infrared band can be maintained below 0.04, which indicates that the parameterized model can be used as the substitute of SAILH model.

(2) Evaluations based on simulated data and measured data show that: from the terms of retrieval absolute error, the retrieval accuracy of the parameterized model is equal to SAILH model; but the retrieval efficiency is improved for 8 ~ 10 times, meanwhile, the stability of the parameterized model is better than SAILH model. However, when we evaluate the retrieval accuracy and efficiency of these models by using the measured data, the expectations and uncertainties of some input parameters are assumed because of no experimental data, which might affect the retrieval results.

(3) Although the parameterized model can make very good approximation to SAILH model in simulating canopy's BRDF, and can greatly improve the efficiency of LAI retrieval while maintaining the retrieval accuracy, this model is based on the assumption that the leaf inclined angle distribution is spherical distribution, and only can be applied to continuous vegetation canopy conditions. Therefore, its applicability is limited to some extent.

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APPENDIX

LAI: Leaf Area Index

θ_s: Sun Zenith Angle φ_s: Sun Azimuth Angle

θ_v: View Zenith Angle φ_v: View Azimuth Angle

θ_m: Average Leaf Inclined Angle ε: Eccentricity

s_L: Hot-spot Effect Factor *Parameter* *skyl*: Ratio of Sky Light

ρ: Leaf Reflectance τ: Leaf Transmittance

ρ_s: Soil Reflectance

面向 LAI 反演的参数化 SAILH 模型

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摘　要: 建立了一种基于植被冠层辐射传输模型 SAILH 的参数化模型。该模型首先对 SAILH 模型中用到的 9 个中间变量的计算过程进行简化, 然后用一个明确的表达式计算光照冠层的单次散射贡献。分别用模拟数据和 2008 年黑河地区星-机-地同步实验中获取的地面测量数据对该参数化模型的反演精度和效率进行了评价。评价结果表明该参数化模型能在保证反演精度的基础上极大的提高反演效率; 利用模拟数据进行的模型稳定性评价表明, 参数化模型的稳定性优于 SAILH 模型。

关键词: SAILH 模型, 参数化, LAI 反演

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1　引　言

叶面积指数 LAI(leaf area index)定义为单位地表面积上方植物叶片单面面积的总和或者总的叶片表面面积的一半(Chen, 1992)。LAI 是一个重要的植被结构参数, 是表征植被冠层结构基本的参量之一, 它与植被的许多生物、物理过程有关, 如光合作用、呼吸作用、蒸腾作用等; 同时, 它反映农作物的长势, 是进行农作物估产的常用参量。

目前利用遥感技术定量反演 LAI 的方法主要有经验统计模型法和物理模型反演法。经验统计模型法是以植被指数作为统计模型的自变量, 建立植被指数与叶面积指数之间的经验统计关系来达到反演 LAI 的目的(方秀琴 & 张万昌, 2003)。这种方法形式比较简单, 需要的参数较少, 是目前常用的主要的 LAI 反演方法, 但是该方法由于缺乏物理基础, 建立的植被指数与叶面积指数之间的统计关系依赖于特定的时间和区域, 不好做时空二维拓展; 物理模型则更接近于现实, 参数具有一定的物理意义, 适用性强, 但是遥感物理模型也存在一定的缺点, 就是其为了能够精确的对地表特征进行描述, 引入了过多的参数, 形式也复杂。虽然多光谱、多角度遥感技术提供了更多的观测信息, 但是遥感反演依然面临着病态问题, 且物理模型的反演速度慢, 不能满足大范围的应用需求。因此寻找一种既具有一定物理含义, 又形式简单的参数化模型对于大面积 LAI 产品的生成具有重要的意义。本文建立了一种基于 SAILH 模型的参数化模型, 然后分别基于模拟数据和黑河地区的实测数据对该参数化模型与 SAILH 模型的反演精度和反演效率进行了评价, 同时利用模拟数据对模型的稳定性进行了评价。

2　SAILH 模型介绍

冠层反射率模型依其建立是否具有理论基础分为经验模型、半经验模型和物理模型 3 类(赵英时, 2007), 物理模型又分为辐射传输模型、几何光学模型、计算机模拟模型等。SAILH 模型是辐射传输模型中的一种。辐射传输模型的基本出发点是辐射传输方程, 辐射传输方程是一个积分–微分方程; 从理

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论上讲，如果确定了边界条件，那么这个方程就是可解的。但是到目前为止，还没有求得辐射传输方程的严格的解析解，只有各种各样的近似解法(徐希孺，2006)。目前应用比较广泛的解法是 Kubelka 和 Munk 提出的 K-M 方程。SAIL(scattering by arbitrarily inclined leaves)(Verhoef, 1984)模型是在 K-M 方程的基础上将入射源分为向上和向下传输的辐射通量密度，以及向上和向下传输的平行辐射辐照度 4 个部分，通过求解 9 个系数(包括直射辐射通量密度的削弱系数(ks)，消光系数(att)，背向散射系数(sig)，直射辐射的前向、后向散射系数(sf, sb)、向上、向下传输的辐射通量密度、向上传输的平行辐射的辐照度向观测方向上传输的辐射亮度的转换系数(uf, ub, ω)、观测方向上的辐射通量密度的削弱系数(ko)进而求得冠层的反射率，因此 SAIL 模型是一个 4 流 9 参数的线性微分方程组。它的输入参数包括 3 个结构参数和 4 个光谱参数。3 个结构参数分别是叶面积指数和描述叶倾角分布的 2 个参数; 4 个光谱参数分别是天空光比例，叶片反射率，叶片透过率和土壤反射率。

由于 SAIL 模型不能很好的对热点效应进行模拟，因此 Kuusk(1991)在 SAIL 模型的基础上加入热点效应从而发展了 SAILH 模型。热点效应是由叶簇对光的一次散射造成的，因此 Kuusk 在 SAIL 模型的基础上通过建立光线方向与观测方向间间隙率的相关概率模型考虑冠层的热点效应。在 SAILH 模型中，整个冠层的单次散射被分解为多层冠层的单次散射贡献之和；在计算每层冠层的单次散射的贡献时，采用了双向透过率密度函数计算其单次散射的贡献。该双向透过率密度函数的计算需要引入一个新的参数——热点效应因子，这样 SAILH 模型的输入参数共 8 个(表 1)。

表 1 SAILH 模型输入参数设置

叶面积指数 LAI	平均叶倾角 θ_m	椭圆离心率 ε	热点效应因子 s_L	天空光比例 skyl	叶片反射率 ρ	叶片透过率 τ	土壤反射率 ρ_s
2	45°	0.1	0.1	0.10	0.08	0.08	0.10

3 参数化模型的建立

在实际应用中，需要不同地表类型的大范围、长时间的 LAI，遥感技术是实现这一目标的途径。大量的研究表明，利用遥感技术可以快速、大范围、周期性地提取区域乃至全球的 LAI，并能够提供 LAI 空间和时间的分布状况(惠凤鸣等，2003)。SAILH 模型虽然是被广泛接受的描述均匀植被冠层方向性反射率的模型，但是其计算过程复杂，反演效率不高，实用性不强。因此以在保证模型反演精度的基础上提高模型的反演效率为目的，对模型进行合理的简化是非常必要的。本文从这个目的出发，提出了一种基于 SAILH 模型的参数化模型，分别基于模拟数据和实测数据对该参数化模型的反演精度、反演效率和程序稳定性进行了评价。

3.1 SAILH 模型中间变量计算过程简化

SAILH 模型的反演效率很低，主要原因是 SAILH 模型在计算冠层反射率时将连续植被冠层的叶倾角离散为 13 个角度，将这 9 个中间变量分别表示为叶倾角的函数，通过对这 13 个角度进行迭代求和计算得到。如果能够将这 9 个中间变量的计算过程简化，其余的计算过程仍然采用 SAILH 模型中的计算过程，那么 SAILH 模型的计算效率会得到提高。通过比较 SAILH 模型中 9 个中间变量的计算过程，得到的简化计算过程如表 2。

在表 2 中，LAI 为叶面积指数，$\mathrm{LAI}'=\dfrac{\mathrm{LAI}}{h}$，$h$ 为冠层高度；θ_l 代表叶倾角，$f(\theta_l)$代表冠层的叶倾角分布密度函数；β_s 和 β_v 分别为光照方向和观测方向的临界角，关于其计算可参见 Verhoef(1984)；$G(\theta_i)(i=\mathrm{s,v})$即为 G 函数(下标 s 代表光照方向，v 代表观测方向)，$\mu_i=\cos\theta_i(i=\mathrm{s,v})$，$\alpha$ 为光照方向与观测方向之间的夹角，计算公式为:

$$\alpha=\cos^{-1}(\mu_s\mu_v+\sin\theta_s\sin\theta_v\cos(\varphi_s-\varphi_v)) \quad (1)$$

在 9 个中间变量中，计算过程最复杂的就是ω，其表示的含义是如果光照方向和观测方向相交于叶片的同侧，则用叶片的反射率表示叶片对光的反射作用；如果光照方向和观测方向相交于叶片的异侧，则用叶片的透过率表示叶片对光的削弱作用。从这个意义上讲，ω表示的是与散射相函数类似的一个概念，不同的是它包含了 LAI，因此在后面的计算中，用散射相函数近似计算 SAILH 中的$\dfrac{\omega}{\mathrm{LAI}}$。

所使用的 SAILH 模型中的叶倾角分布函数是用双参数椭圆分布描述的，为了能够对该分布的叶倾角的散射相函数进行比较好的近似，选择用球形分布的散射相函数代替$\dfrac{\omega}{\mathrm{LAI}}$。此时，当$\varepsilon\leqslant 0.9$ 时能得到比较好的近似结果，但当叶倾角分布为极端型的情况时，近似的结果就会出现偏差。当叶倾角分布近似为垂直型时，引入的相对误差为 30%；近似为

水平型时, 引入的相对误差为 20%。图 1 给出了当模型的输入参数设置如表 1 所示时(红光波段)SAILH 模型和参数化模型计算 9 个中间变量的结果比较, 其中将太阳天顶角设置为 35°, 观测天顶角从 0°到 60°以 10°的角度间隔变化, 二者的相对方位角设置为 0°(代表太阳主平面)。由图 1 看出, 在红光波段, 如果不考虑极端型叶倾角分布, 参数化模型与 SAILH 模型计算 9 个中间变量的结果非常接近; 对于近红外波段得到了同样的结果。图 1 中观测天顶角的负值代表后向观测。

3.2　光照冠层单次散射的贡献

假设连续植被冠层由一系列的水平的均匀层叠加而成, 各层之间相互独立, 那么整个冠层对直射光的单次散射的贡献 P_c^1 为(Kuusk, 1991):

$$P_c^1 = \frac{\Gamma(\Omega_s,\Omega_v)}{\mu_s \mu_v}\int_0^H u_L(z)P(z,\Omega_s,\Omega_v)\mathrm{d}z \tag{2}$$

表 2　SAILH 及参数化模型 9 个参数计算公式

	SAILH 模型(Verhoef, 1984)	参数化模型
att	$\sum\left(\mathrm{LAI}'\times\left(1-\frac{\rho+\tau}{2}+\frac{\rho-\tau}{2}\times\cos^2\theta_l\times f(\theta_l)\right)\right)$	$\mathrm{LAI}\times\left(1-\frac{\rho+\tau}{2}+\frac{\rho-\tau}{2}\times\sum(\cos^2\theta_l\times f(\theta_l))\right)$
sig	$\sum\left(\mathrm{LAI}'\times\left(\frac{\rho+\tau}{2}+\frac{\rho-\tau}{2}\times\cos^2\theta_l\times f(\theta_l)\right)\right)$	$\mathrm{LAI}\times\left(\frac{\rho+\tau}{2}+\frac{\rho-\tau}{2}\times\sum(\cos^2\theta_l\times f(\theta_l))\right)$
sf	$\sum\left(\frac{\rho+\tau}{2}\times \mathrm{ks}(\theta_l)-\frac{\rho-\tau}{2}\times\mathrm{LAI}'\times\cos^2\theta_l\times f(\theta_l)\right)$	$\frac{\rho+\tau}{2}\times\frac{G(\theta_s)\times\mathrm{LAI}}{\mu_s}-\frac{\rho-\tau}{2}\times\mathrm{LAI}\times\sum(\cos^2\theta_l\times f(\theta_l))$
sb	$\sum\left(\frac{\rho+\tau}{2}\times \mathrm{ks}(\theta_l)+\frac{\rho-\tau}{2}\times\mathrm{LAI}'\times\cos^2\theta_l\times f(\theta_l)\right)$	$\frac{\rho+\tau}{2}\times\frac{G(\theta_s)\times\mathrm{LAI}}{\mu_s}+\frac{\rho-\tau}{2}\times\mathrm{LAI}\times\sum(\cos^2\theta_l\times f(\theta_l))$
ks	$\sum\left(\frac{2}{\pi}\times\mathrm{LAI}'\times\left[(\beta_s-\frac{\pi}{2})\cos\theta_l+\sin\beta_s\tan\theta_s\sin\theta_l\right]\times f(\theta_l)\right)$	$\frac{G(\theta_s)\times\mathrm{LAI}}{\mu_s}$
ko	$\sum\left(\frac{2}{\pi}\times\mathrm{LAI}'\times\begin{bmatrix}(\beta_v-\frac{\pi}{2})\cos\theta_l+\\ \sin\beta_v\tan\theta_v\sin\theta_l\end{bmatrix}\times f(\theta_l)\right)$	$\frac{G(\theta_v)\times\mathrm{LAI}}{\mu_v}$
uf	$\sum\left(\frac{\rho+\tau}{2}\times \mathrm{ko}(\theta_l)-\frac{\rho-\tau}{2}\times\mathrm{LAI}'\times\cos^2\theta_l\times f(\theta_l)\right)$	$\frac{\rho+\tau}{2}\times\frac{G(\theta_v)\times\mathrm{LAI}}{\mu_v}-\frac{\rho-\tau}{2}\times\mathrm{LAI}\times\sum(\cos^2\theta_l\times f(\theta_l))$
ub	$\sum\left(\frac{\rho+\tau}{2}\times \mathrm{ko}(\theta_l)+\frac{\rho-\tau}{2}\times\mathrm{LAI}'\times\cos^2\theta_l\times f(\theta_l)\right)$	$\frac{\rho+\tau}{2}\times\frac{G(\theta_v)\times\mathrm{LAI}}{\mu_v}+\frac{\rho-\tau}{2}\times\mathrm{LAI}\times\sum(\cos^2\theta_l\times f(\theta_l))$
ω	见 verhoef(1984)	$\frac{\rho+\tau}{3\pi}\times(\sin\alpha-\alpha\times\cos\alpha)+\frac{\rho}{3}\times\cos\alpha$

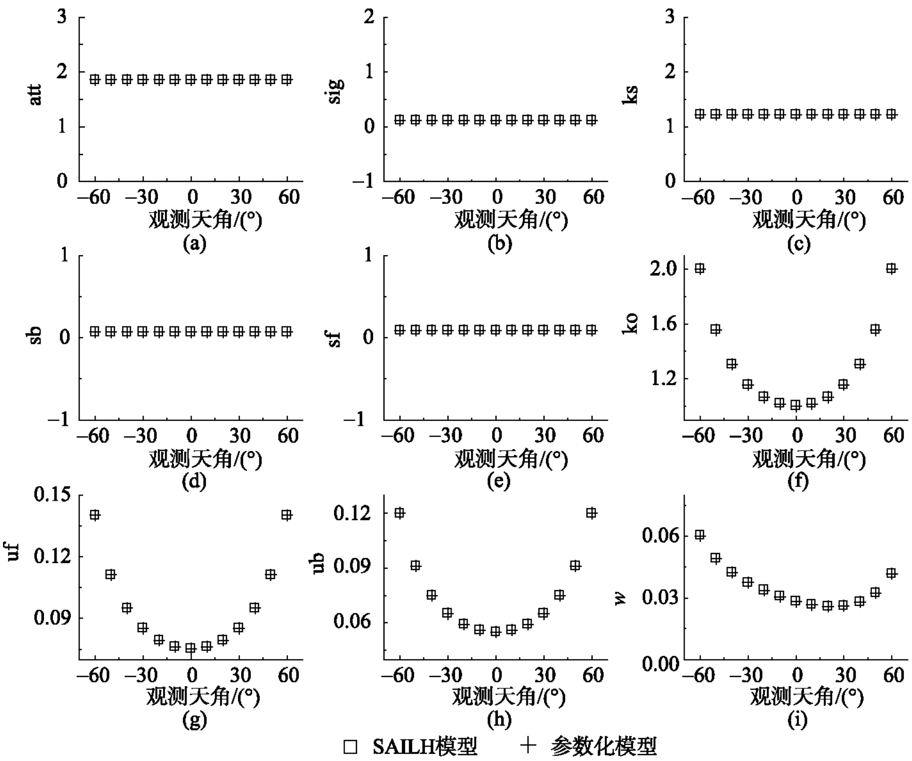

图 1　SAILH 模型和参数化模型计算 9 个中间变量比较

(a) att; (b) sig; (c) ks; (d) sb; (e) sf; (f) ko; (g) uf; (h) ub; (i) *w*

式中，$\Gamma(\Omega_s,\Omega_v)$为散射相函数，$u_L(z)$为叶面积体密度，$P(z,\Omega_s,\Omega_v)$为双向透过率密度函数，计算公式为:

$$P(z,\Omega_s,\Omega_v)=P_s(z)P_v(z)C_{HS}(z,\Omega_s,\Omega_v) \quad (3)$$

式中，$P_s(z)$和 $P_v(z)$分别代表太阳方向和观测方向在冠层高度 z 处的平均透过率(计算公式用 ks 和 ko)，$C_{HS}(z,\Omega_s,\Omega_v)$为热点因子，关于其计算可参见 Kuusk(1991)的文章。SAILH 模型中在对式(2)进行积分时，假设叶面积体密度 $u_L(z)$不随高度变化，将其作为一个常数提到了积分号外面(LAI′)并参与到 9 个中间变量的计算过程中，然后只对双向透过率密度函数 $P(z,\Omega_s,\Omega_v)$进行积分。由于该积分不能得到明确的解析表达式，所以模型中采用了 Simpson 积分的方法，把整个冠层离散为 20 层，将这 20 层的和作为积分的结果；但是如果直接对$\int_0^H u_L(z)P(z,\Omega_s,\Omega_v)dz$进行积分就可以得到一个计算光照冠层单次散射的解析表达式，计算结果为:

$$P_c=\frac{1-P_g}{a_s+a_v-\sqrt{a_s a_v}\times\frac{s\_L}{\Delta}\times(1-\exp(-\frac{\Delta}{s\_L}))} \quad (4)$$

式中，P_g代表可见光照土壤的面积比例，通过对式(3)进行积分得到，P_g的计算结果如下(Kuusk, 1991):

$$P_g=\exp(-(a_s+a_v-\sqrt{a_s a_v}\times\frac{s\_L}{\Delta}\times(1-\exp(-\frac{\Delta}{s\_L})))\times LAI) \quad (5)$$

其中:

$$a_i=\frac{G(\theta_i)}{\mu_i}(i=s,v) \quad (6)$$

s_L 为热点效应因子，Δ的计算公式如下:

$$\Delta=\sqrt{\frac{1}{\mu_s^2}+\frac{1}{\mu_v^2}-\frac{2\cos\alpha}{\mu_s\mu_v}} \quad (7)$$

为了检验式(4)的计算结果是否正确，将其与 SAILH 模型的计算结果比较，如图 2。P_c代表式(4)的计算结果，标记为 20 的曲线代表将冠层离散为 20 层时 SAILH 模型的计算结果；同理，标记为 50、100 的曲线分别表示将冠层离散为 50 层、100 层时 SAILH 模型的计算结果。由图 2 看出，将冠层离散的层数越多，SAILH 模型的计算结果与式(4)的计算结果就越接近，由此也证明了式(4)的正确性。

得到了 P_c的表达式，那么整个冠层对直射光的单次散射就可以表示为:

$$P_c^1=\frac{\Gamma(\Omega_s,\Omega_v)}{\mu_s\mu_v}P_c \quad (8)$$

至此，9 个中间变量及光照冠层单次散射贡献的计算过程已得到简化，其余的计算过程仍然使用 SAILH 的计算过程。

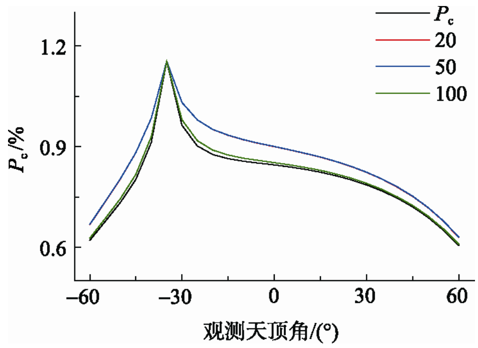

图 2 式(4)计算结果正确性检验

设计了一组简单的实验参数化模型正向模拟 BRDF 的能力进行评价和比较。假设太阳天顶角为 35°；太阳方位角为 0°；观测天顶角从 0°—85°，以 5°的角度间隔变化；观测方位角从 0°—355°，同样以 5°的角度间隔变化；这样整个上半球空间总共有 1296 个观测角度组合。结构参数的输入值如表 3。

表 3 正向模拟 BRDF 能力比较时结构参数设置

组	组数	LAI	θ_m/(°)	ε	s_L
第 1 组	1	2	45	0.001	0.1
	2	4	45	0.001	0.1
第 2 组	3	2	0.001	0.9	0.1
	4	2	35	0.9	0.1
	5	2	65	0.9	0.1
	6	2	89.9	0.9	0.1
第 3 组	7	4	0.001	0.9	0.1
	8	4	35	0.9	0.1
	9	4	65	0.9	0.1
	10	4	89.9	0.9	0.1

参数的设计是出于以下 3 个方面的考虑:

(1) 第 1 组：将椭圆离心率ε设定为 0.001，这种情况下叶倾角的分布接近于球形分布，分别比较当 LAI=2 和 LAI=4 时参数化模型正向模拟 BRDF 的能力；

(2) 第 2 组：将椭圆离心率ε设定为 0.9，平均叶倾角θ_m设定为不同的值，其中当θ_m=0.001°时可近似代表平面型分布的叶倾角分布，θ_m=89.9°时可近似代表垂直型分布的叶倾角分布，θ_m=35°和θ_m=65°代表两种过渡情况，然后比较当 LAI=2 时参数化模型的正向模拟能力；

(3) 第 3 组：其他参数设置同(2)，比较当 LAI=4 时参数化模型的正向模拟能力。对于光谱参数，将红光波段的天空光比例、叶片的反射率、叶片透过率和土壤反射率分别固定为 0.1, 0.1, 0.12 和 0.1，近红外波段的值则分别固定为 0.1, 0.45, 0.5 和 0.2。

对参数化模型的模拟能力进行评价的指标为参

数化模型与SAILH模型正向模拟的整个上半球空间的 BRDF 之间的均方根误差(RMSE)和相关系数，得到的结果如表 4。通过分析知道，在整个上半球空间，参数化模型与 SAILH 模型正向模拟 BRDF 的 RMSE 在红光波段能保持在 0.01 以下，在近红外波段能保持在 0.04 以下，不管在红光还是近红外波段，参数化模型与 SAILH 模型的相关系数达到了 96%以上。

表 4　参数化模型模拟 **BRDF** 能力评价

组数	均方根误差 RMSE		相关系数	
	红光波段	近红外波段	红光波段	近红外波段
1	0.00341	0.01192	0.97911	0.99838
2	0.00554	0.02204	0.99075	0.99398
3	0.00475	0.02739	0.98855	0.99482
4	0.00443	0.02367	0.98751	0.99431
5	0.00280	0.00662	0.97596	0.99719
6	0.00253	0.01169	0.96194	0.99051
7	0.00784	0.03958	0.98945	0.97686
8	0.00727	0.03550	0.99119	0.97877
9	0.00441	0.01243	0.98723	0.99417
10	0.00374	0.01104	0.97549	0.98451

4　模型评价

参数化模型与SAILH模型正向模拟的BRDF之间有很高的相关性，可以说参数化模型对 SAILH 模型具有一定的代表性。

4.1　基于模拟数据的模型评价

模拟数据的生成过程如下：假设一组或几组输入参数，给定相应的先验知识，以 SAILH 模型的前向模拟值作为观测真值，采用鲍威尔(Powell)优化算法对参数化模型反演。为了便于比较，在相同的先验知识下，同时用 SAILH 模型反演各种情况下的 LAI 值。反演过程中对观测真值加入 10%的高斯噪声。

4.1.1　模型反演精度评价

模型反演精度的评价是以反演结果与 LAI 前向模拟输入值之间的绝对误差为评价标准的。图 3 表示了 LAI 前向模拟输入值与 LAI 反演值之间的关系。图 4 表示了反演的绝对误差随 LAI 前向模拟输入值大小变化的关系。

由图 3 和图 4 看出，该参数化模型的反演精度与 SAILH 模型相比，没有太大程度的损失；从绝对误差看，SAILH 模型在红光波段的最大反演误差为 0.180，近红外波段的最大反演误差为 0.122；而参数化模型在红光波段的最大反演误差为 0.179，近红外波段的最大反演误差为 0.197。

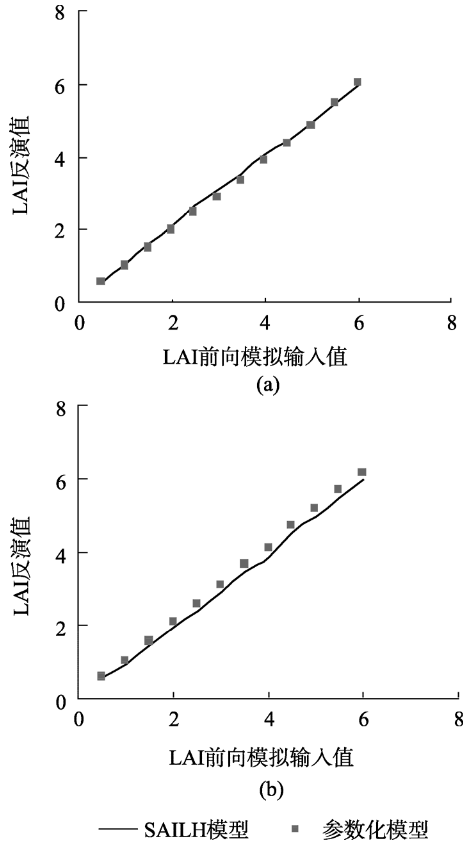

图 3　LAI 反演值与前向模拟输入值比较
(a) 红光波段; (b) 近红外波段

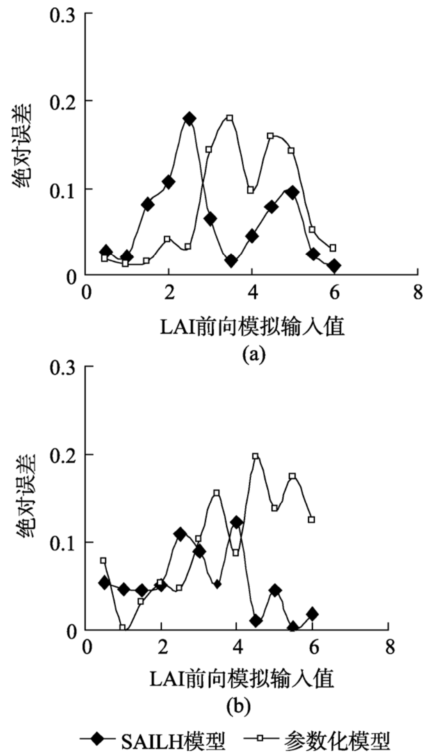

图4　反演绝对误差随LAI前向模拟输入值大小变化关系
(a) 红光波段; (b) 近红外波段

4.1.2 模型反演效率评价

在对模型的反演效率进行评价时采取的方法为：每次反演实验均使用 6 个角度的观测数据，在反演中设置不同的反演次数，分别为 50、100、200 和 500 次，计算模型运行的时间；每次实验重复 5 次，然后取这 5 次实验的平均值作为模型反演效率的评价标准，得到的结果如图 5。由图 5 看出，在反演效率方面，参数化模型较 SAILH 模型有了明显的提高，将反演效率提高了 10 倍。

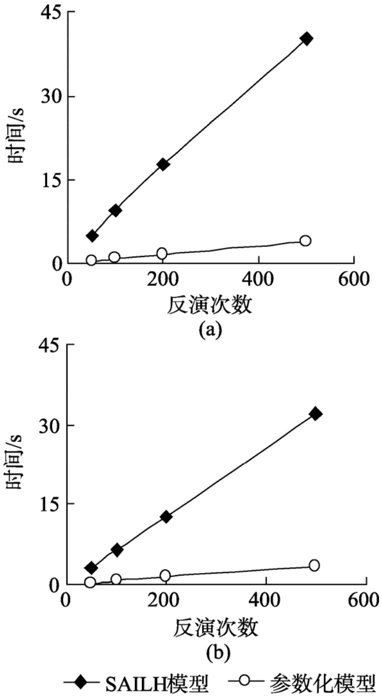

图 5 参数化模型与 SAILH 模型反演效率比较
(a) 红光波段; (b) 近红外波段

4.1.3 模型稳定性评价

对于模型稳定性的评价，我们采用了下面的方法：在反演过程中，通过增大加入模拟数据中的噪声，比较其对 LAI 反演精度的影响(以相对误差作为评价标准)，得到的结果如图 6 所示。由图 6 可以看出，SAILH 模型和参数化模型的 LAI 反演误差都随着加入噪声的增大而增大；不管是在红光波段还是近红外波段，参数化模型的稳定性整体上优于 SAILH 模型。

4.2 基于实测数据的模型评价

利用 2008 年黑河地区星-机-地同步实验中获得的盈科站玉米冠层反射率和 LAI 地面测量数据对参数化模型评价。实验区在 2008-06-22 和 2008-07-01 分别有 2 次测量数据，2008-07-09 只有 1 次测量数据，总共有 5 组地面测量数据。反演时同样采用鲍威尔

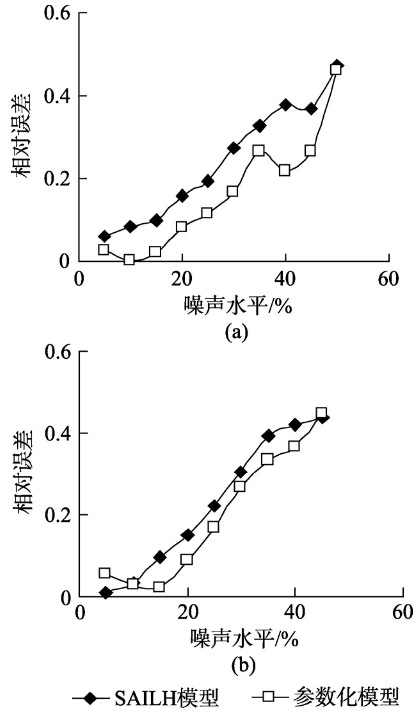

图 6 参数化模型与 SAILH 模型稳定性比较
(a) 红光波段; (b) 近红外波段

优化算法进行反演，同时反演 8 个参数。在模型的输入参数中，叶面积指数、叶片反射率、叶片透过率及土壤反射率的期望值及不确定性均由地面实测数据得到；平均叶倾角和椭圆离心率 2 个参数的期望值由实测 LAD 数据反演得到，不确定性设置为 0.01；热点效应因子和天空光比例 2 个参数的期望值和不确定性分别设置为 0.1 和 0.01。输入参数值及其不确定性的详细设置如表 5。

表 5 输入参数值及先验知识设置

输入参数	红光波段		近红外波段	
	期望值	不确定性	期望值	不确定性
LAI	3	0.4	3	0.4
θ_m	45°	0.01	45°	0.01
ε	0.6	0.01	0.6	0.01
s_L	0.1	0.01	0.1	0.01
skyl	0.1	0.01	0.1	0.01
ρ	0.08	0.01	0.45	0.03
τ	0.05	0.01	0.5	0.03
ρ_s	0.17	0.01	0.2	0.03

4.2.1 模型反演精度比较

在黑河试验的地面测量中，除 2008-07-09 外，每次测量分别测量了太阳主平面、垂直主平面、平行垄平面和垂直垄平面 4 个平面的冠层反射率(2008-07-09 只有太阳主平面和垂直主平面 2 个平面的测量数据)。在反演实验中，首先用各个平面的测量数据分别反演 LAI，然后用 4 个平面所有的数据

共同反演 LAI。最终, 得到下面的结果: 与地面实测值相比, SAILH 模型的反演最大绝对误差为 1.344, 最小绝对误差为 0.002; 参数化模型的反演最大绝对误差为 0.807, 最小绝对误差为 0.056。由此可见, 参数化模型的反演误差在可接受的范围内。

4.2.2 模型反演效率比较

同时利用实测数据对参数化模型的反演效率进行了评价, 同样得到了参数化模型在反演效率上较 SAILH 模型有很大提高的结论, 参数化模型将反演效率提高了大约 8—10 倍。

5 结论与讨论

建立了一种基于 SAILH 模型的参数化模型, 该模型对 SAILH 模型中 9 个中间变量的计算过程进行了简化, 同时简化了光照冠层单次散射贡献的计算过程, 其余的计算过程仍采用 SAILH 模型中的计算公式; 然后利用模拟数据和实测数据对参数化模型的反演精度、反演效率和稳定性进行了评价, 得到的结论如下:

(1) 在整个上半球空间, 参数化模型正向模拟 BRDF 的能力与 SAILH 模型有很强的相关性, 在红光和近红外两个波段的相关系数均达到了 96%以上, RMSE 在红光波段能保持在 0.01 以下, 在近红外波段能保持在 0.04 以下, 说明该参数化模型可以替代 SAILH 模型;

(2) 基于模拟数据和实测数据的模型评价表明, 从反演 LAI 的绝对误差看, 该参数化模型在反演精度上与 SAILH 模型的精度相当, 而反演效率则较 SAILH 模型提高了 8—10 倍; 同时参数化模型的稳定性也优于 SAILH 模型。但由于在利用实测数据进行模型反演精度和效率的评价时, 部分输入参数的期望值和不确定性由于没有实测数据而人为假设, 因此可能会对反演结果造成影响。

(3) 虽然该参数化模型能够对 SAILH 模型前向模拟 BRDF 的能力进行很好的近似, 并能在保证反演精度的基础上极大的提高 LAI 的反演效率, 但是该模型的建立是基于叶倾角分布为球形分布的假设, 且只适用于连续植被冠层的情况, 因此其适用性受到了一定程度的限制。

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