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OPTICAL MODELS AND DATABASES

Software Package for Reconstructing Reflective Properties of the Earth's Surface in the Visible and UV ranges

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Abstract—A description of a software package for reconstructing the distribution of the reflection coefficient of the Earth's surface, as well as procedures developed for a considerable reduction of the computation time, is presented. By an example of a test region in the western coast of Africa, a comparison has been performed for results obtained by the proposed algorithm, the algorithm of homogeneous correction, and the standard MOD09 NASA algorithm. The correlation coefficients of results for this test region are as follows: between the new algorithm and homogeneity correction algorithm, 0.999; between the new algorithm and the MOD09 algorithm, 0.984.

Keywords: Monte Carlo method, atmospheric correction, radiative transfer equation

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INTRODUCTION

Knowledge of the reflection coefficients of the Earth's surface is in common use in such problems as territory mapping, the search for deposits, monitoring of the state of forests, etc. Satellite information is one of main (in many cases, almost unique) sources of such data. This is connected with the inclusiveness of satellite systems. However, using satellite data has its own specificity. One of the key problems in using satellite data is the elimination of the atmospheric effect or the atmospheric correction. At present, there are several approaches to solving this problem, e.g., [1–3]; however, each of them has its own restrictions. To take into account all necessary factors having an effect on the formation of an image in the visible and UV ranges, an atmospheric correction algorithm described in [4] was developed. In this work, reconstructed reflection coefficients of the Earth's surface are compared for a test area on the Earth's surface with the aim to compare the developed algorithm with results of the MOD09 algorithm used in NASA.

PROCESSES FORMING IMAGES IN THE VISIBLE AND UV RANGES

Radiative transfer in the wavelength range under consideration has a complex nature in the general case. The radiation received by a satellite system in most complicated optical situations includes the following (Fig. 1a):

(1) The intensity of the solar haze $I_\odot$ (solar radiation scattered in the atmosphere and not interacting with the Earth's surface), which can constitute a considerable part of the received radiation under conditions of strong turbidity or optically dense cloudiness;

(2) The intensity I_0 of nonscattered radiation attenuated by the atmosphere from the observed area of the Earth's surface;

(3) The intensity I_{surf} of the scattered radiation from the Earth's surface reflected by the observed area and rest surface (surface haze or adjacency effect).

Illumination of the Earth's surface by the Sun in this process is also of a complex nature. The total illumination is formed not only by the direct and diffuse solar radiation E_0 but also by the radiation E_1 that illuminated the Earth's surface again after the reflection from it (rereflected radiation) (Fig. 1b). The rereflection process occurs multiply and gradually decreases by geometric progression with a coefficient γ_1 at the reflection coefficient of the Earth's surface $r_{\mathrm{surf}} = 1$.

CALCULATION ALGORITHM

The problem is solved in the following statement (Fig. 2).

A passive satellite system is positioned at the altitude h_d from the spherical Earth's surface. It is oriented in the direction $\boldsymbol{\omega}_d = (\theta_d, \varphi_d)$ and observes an area of the

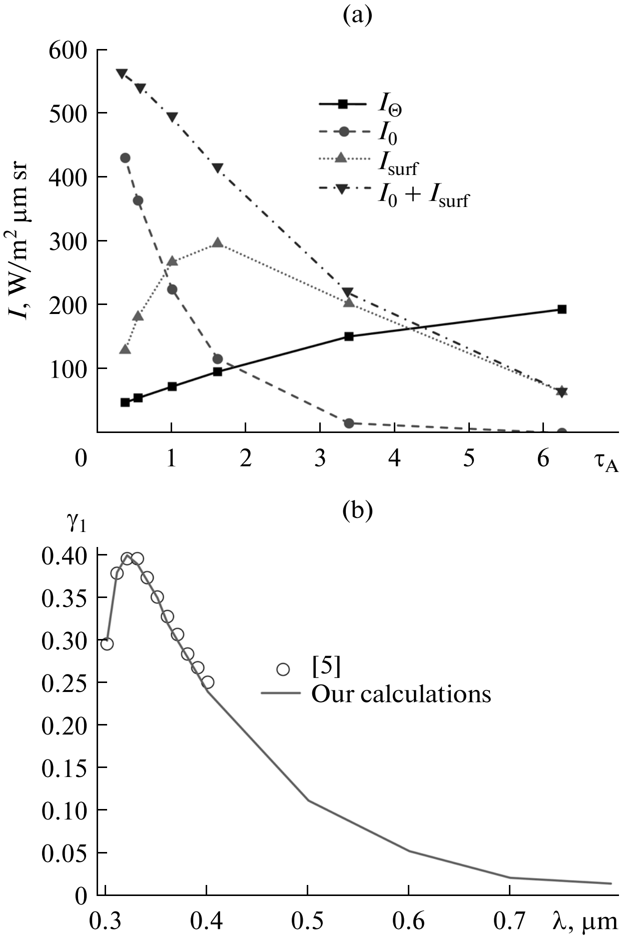

Fig. 1. (a) Radiation components at $\lambda = 0.47$ μm, meteorological visibility range $S_M = 1$–50 km, and zenith angle of the Sun $\theta_\odot = 0°$. Observations to the nadir ($\theta_d = 0°$), $r_{surf} = 1$. Optical models are specified using the LOWTRAN-7 generator [6]; (b) contribution of the singly rereflected radiation to the illumination γ_1 as a function of the wavelength at $r_{surf} = 1$ for a molecular atmosphere.

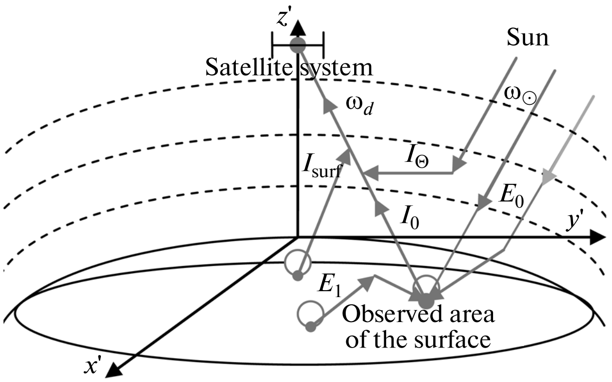

Fig. 2. Problem geometry.

Earth's surface. The Earth's surface is Lambertian with an unknown distribution of the reflection coefficient. The spatial resolution of the optical receiver is assumed to be constant within the limits of the observed area. A solar radiation flux falls on the upper boundary of the atmosphere in the direction $\boldsymbol{\omega}_\odot$. Knowing optical parameters of the atmosphere and intensity measured by the satellite system, it is required to reconstruct the reflection coefficient r_{surf}.

The solution of the problem is constructed as follows [4]. The intensity I_{sum} of the radiation received by the satellite system is the sum

$$I_{sum} = I_0 + I_\odot + I_{surf}. \tag{1}$$

To find r_{surf}, if it is assumed that the surface is homogeneous within a pixel, radiation components vary insignificantly, and only the additional illumination of the Earth's surface of the first multiplicity is taken into account, it is necessary to solve a nonlinear system of equations [4]. The solution of the system consists of two stages. At the first stage, the quantity $Q = r_{surf}E_{sum}$ is found from the system of equations

$$\begin{cases} I_{sum}(x_{w,1}, y_{w,1}) - I_\odot(x_{w,1}, y_{w,1}) \\ = \dfrac{Q_1\mu_1}{\pi}\exp(-\tau_1) + \sum\limits_{k=1}^{N} Q_k H_{k,1}, \\ \dots \\ I_{sum}(x_{w,N}, y_{w,N}) - I_\odot(x_{w,N}, y_{w,N}) \\ = \dfrac{Q_N\mu_N}{\pi}\exp(-\tau_N) + \sum\limits_{k=1}^{N} Q_k H_{k,N}, \end{cases} \tag{2}$$

$$H_{k,i} = \iint\limits_{S_k} h_i\left(x'_w - x_{w,i}, y'_w - y_{w,i}\right)dx'_w dy'_w, \tag{3}$$

where μ is the cosine of the angle between the direction to the receiving system and a vertical at the observed point of the surface; τ is the optical length of the path; h_i is the point spread function (PSF) of the channel forming the adjacency effect in the process of observing the ith point; and $H_{k,i}$ is the surface integral of the kth pixel S_k of the PSF of the channel forming the adjacency effect in the process of observing the ith pixel.

At the second stage, the reflection coefficient is determined from the nonlinear system of the form

$$\begin{cases} \dfrac{Q_1}{E_0} = r_{surf,1}\left(1 + \sum\limits_{l=1}^{N} r_{surf,l}P_l\right), \\ \dots \\ \dfrac{Q_N}{E_0} = r_{surf,N}\left(1 + \sum\limits_{l=1}^{N} r_{surf,l}P_l\right), \end{cases} \tag{4}$$

$$P = \iint\limits_{S_l} p\left(x'_w - x_w, y'_w - y_w\right) dx'_w dy'_w. \tag{5}$$

Here, $r_{\mathrm{surf},i}$ is the sought value of the reflection coefficient in the ith pixel of the image; p is the PSF of the channel forming the additional illumination; and P_l is the integral over the surface of the lth pixel of the PSF of the channel forming the additional illumination.

If large rereflection multiplicities must be taken into account, it is proposed to do this in the homogeneous approximation. In this case, the reflection coefficient is determined by the formula

$$r_{\mathrm{surf},i} \approx \frac{\tilde{r}_{\mathrm{surf},i}(1 + \tilde{r}_{\mathrm{surf},i}\gamma_1)}{1 + \tilde{r}_{\mathrm{surf},i}\gamma_1(1 + \tilde{r}_{\mathrm{surf},i}\gamma_1)}, \tag{6}$$

where $r_{\mathrm{surf},i}$ is the reflection coefficient value obtained with allowance for an infinite number of rereflection multiplicities, $\tilde{r}_{\mathrm{surf},i}$ are results of solution of system (4); and γ_1 is the contribution of the singly rereflected radiation to the illumination of the Earth's surface at $r_{\mathrm{surf}} = 1$.

The implementation of this requires significant consumptions of computing time; for this reason, in [4], to accelerate the computation, it is proposed to use the following.

1. *Criterion of Image Isoplanarity*

An image can be divided into zones specified by the angle θ_d so that the PSF can be considered as constant with in each of them. To determine them, the following criterion for distinguishing isoplanar zones was proposed in [7]:

$$\begin{cases} \theta_{d,i+1} \\ = \arccos\left(1 - \left(\left(m_{00}(0^0) - \dfrac{m_{00}(\theta_{d,i})}{1+\delta}\right)\Big/\exp(A)\right)^{1/N}\right); \\ m_{00}\left(\theta_{d,i}\right) = m_{00}(0^0) - \exp(A)(1 - \cos\theta_{d,i})^N, \end{cases} \tag{7}$$

$$m_{00}(\theta_{d,i}) = \frac{\mu_i}{\pi}\exp(-\tau_i) + \iint\limits_S h(x'_w, y'_w, \theta_{d,i}) dx'_w dy'_w.$$

Here, A and N are the approximation constants determined by the least squares method according to nodal values in the integral of the PSF of the channel forming the adjacency effect. The nodal values were obtained using the algorithm described in [8]; δ is the order of the error in specifying the isoplanar zones.

2. *Adjacency Effect Radius*

In many cases, the function h is a rapidly decreasing function; therefore, it is reasonable to restrict the integration domain in (3) by the adjacency effect radius R_{surf} (the radius is regarded in surface coordinates). To specify R_{surf}, it is proposed to use the condition of the form [4]

$$k_i(R_{\mathrm{surf},i}) \geq \delta_1 + (\delta_1 - 1)\frac{\mu_i\exp(-\tau_i)/\pi}{H_i}, \tag{8}$$

where

$$k_i(R_{\mathrm{surf}}) = \frac{\iint\limits_{S(R_{\mathrm{surf}})} h_i(x'_w - x_w, y'_w - y_w) dx'_w dy'_w}{H(x_w, y_w)}; \tag{9}$$

$$H(x_w, y_w) = \iint\limits_S h(x'_w - x_w, y'_w - y_w) dx'_w dy'_w. \tag{10}$$

Here, k_i, $R_{\mathrm{surf},\,i}$, τ_i, H_i, and μ_i correspond to the ith isozone; δ_1 specifies the accuracy of determining Q (we used $\delta_1 = 0.99$); $S(R_{\mathrm{surf}})$ is the area of the Earth's surface within the limits of R_{surf}; and S is the entire Earth's surface.

3. *Radius of the Rereflection Influence Area*

By virtue of the rapid decrease of the function p, the domain of integration in (5) can be restricted by the radius of the rereflection formation R_1. To estimate R_1, it is proposed to use the condition [4]:

$$k_1(R_1) \geq \frac{\delta_2}{\gamma_1}\left(\frac{\delta_2}{1-\gamma_1} - 1\right), \tag{11}$$

where

$$k_1(R_1) = \frac{\iint\limits_{S(R_1)} p(x'_w - x_w, y'_w - y_w) dx'_w dy'_w}{\iint\limits_S p(x'_w - x_w, y'_w - y_w) dx'_w dy'_w}; \tag{12}$$

and δ_2 is the required accuracy of determining the reflection coefficient.

4. *Formula for the Solar Haze Intensity*

In [9], to describe the dependence of $I_\odot$ on the angle of satellite system orientation, it is proposed to use the formula

$$I_\odot(\theta_d, \varphi_d) = -\frac{B + \sqrt{B^2 - 4AC_{13}}}{2A\cos\theta_d}, \tag{13}$$

where

$$\begin{aligned} A &= C_{11}\cos^2\theta_d + C_{i1}(\sin\theta_d\cos\varphi_d)^2 \\ &+ C_{i2}\cos\theta_d\sin\theta_d\cos\varphi_d - (\sin\theta_d\sin\varphi_d)^2; \end{aligned} \tag{14}$$

$$B = C_{12}\cos\theta_d + C_{i3}\sin\theta_d\cos\varphi_d; \tag{15}$$

θ_d is the zenith angle at which the optical system axis is oriented; φ_d is the azimuthal angle between the direction to the Sun and axis of the optical system; C_{11},

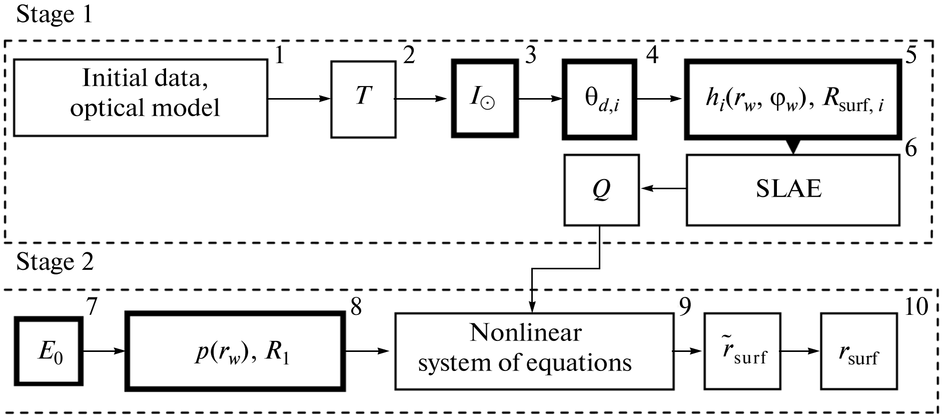

Fig. 3. Control-flow chart of the software package.

C_{12}, C_{13}, C_{21}, C_{22}, C_{23}, C_{31}, C_{32}, and C_{33} are the constants obtained by approximation of nodal calculations of solar haze intensity by the Monte Carlo method for nodal directions $\theta_d = 0, 15, ..., 60°$ and $\varphi_d = 0, 30, ..., 180°$ (35 nodes).

SOFTWARE PACKAGE FOR ATMOSPHERIC CORRECTION

Based on the algorithm described above, a software package was developed for atmospheric correction of satellite data in the visible and UV ranges. The control-flow chart is shown in Fig. 3. The calculation is organized as follows.

1. Satellite data about the mutual position of the center of the observed area, satellite system, and the Sun, measurements of the received radiation intensity in the given channel of the MODIS satellite are read, as well as data on the aerosol optical depth (AOD) τ_A of the area under consideration. Among models generated by LOWTRAN-7 [6], one chooses a model that is the closest in the AOD; it specifies the profile of optical parameters in the atmosphere.

2. The transmission coefficient T is calculated.

3. Using the Monte Carlo method, the solar haze intensity $I_{\odot}$ is calculated for 35 nodal directions; using the least squares method, the approximation constants $C_{11}, ..., C_{33}$ are found and approximate values of $I_{\odot}$ are found by formulas (13)–(15) for each image pixel.

4. Using the Monte Carlo method, nodal values of the integral of the PSF are calculated for receiver zenith angles of 0, 15, ..., 60°. Using the least squares method, the approximation constants A and N are found, and using criterion (7), boundaries of isoplanar zones $\theta_{d,i}$.

5. By formulas (8)–(10), R_{surf} is calculated. For each isoplanar zone, its own point spread function of the channel forming the adjacency effect $h_i(r_w, \varphi_w)$ is calculated by the Monte Carlo method within its $R_{\mathrm{surf},\,i}$ ((r_w, φ_w) are the surface polar coordinates).

6. Coefficients of system of linear algebraic equations (2) are calculated. Using the method of solving the system of linear algebraic equations (SLAE), values of the Earth's surface luminosity Q are found.

7. Using the Monte Carlo method, the Earth's illumination is calculated without regard to rereflections E_0.

8. Using formulas (11) and (12), R_1 is calculated. Using the Monte Carlo method, the PSF of the channel forming the additional illumination by the rereflection $p(r_w)$ within the limits of the radius R_1 is calculated.

9. Coefficients entering in system (4) are calculated and nonlinear system of equations (4) is solved. Coefficients $\tilde{r}_{\mathrm{surf}}$ are the solution of this system.

10. The second and larger multiplicities of rereflection are taken into account by formula (6) and the sought value r_{surf} is found.

The correction algorithm was tested in [4]. The performed series of calculations showed that, on the one hand, Monte Carlo algorithms used in the computations yield results agreeing with published data; on the other hand, the developed algorithm, in contrast to other algorithms, allows one to reconstruct reflection coefficients with a sufficient accuracy in the case of sudden drops in the reflection coefficient and high turbidity. According to test calculations [4], using the techniques described above reduces the computation time by more than six times.

COMPARING THE RESULTS BY AN EXAMPLE OF A TEST AREA OF THE EARTH'S SURFACE

Comparing the calculation results obtained by the proposed algorithm with those obtained by the MOD09 algorithm [2] and homogeneity correction algorithm [10] for a test area of the Earth's surface was the next stage of testing. As a test area, a region in the western

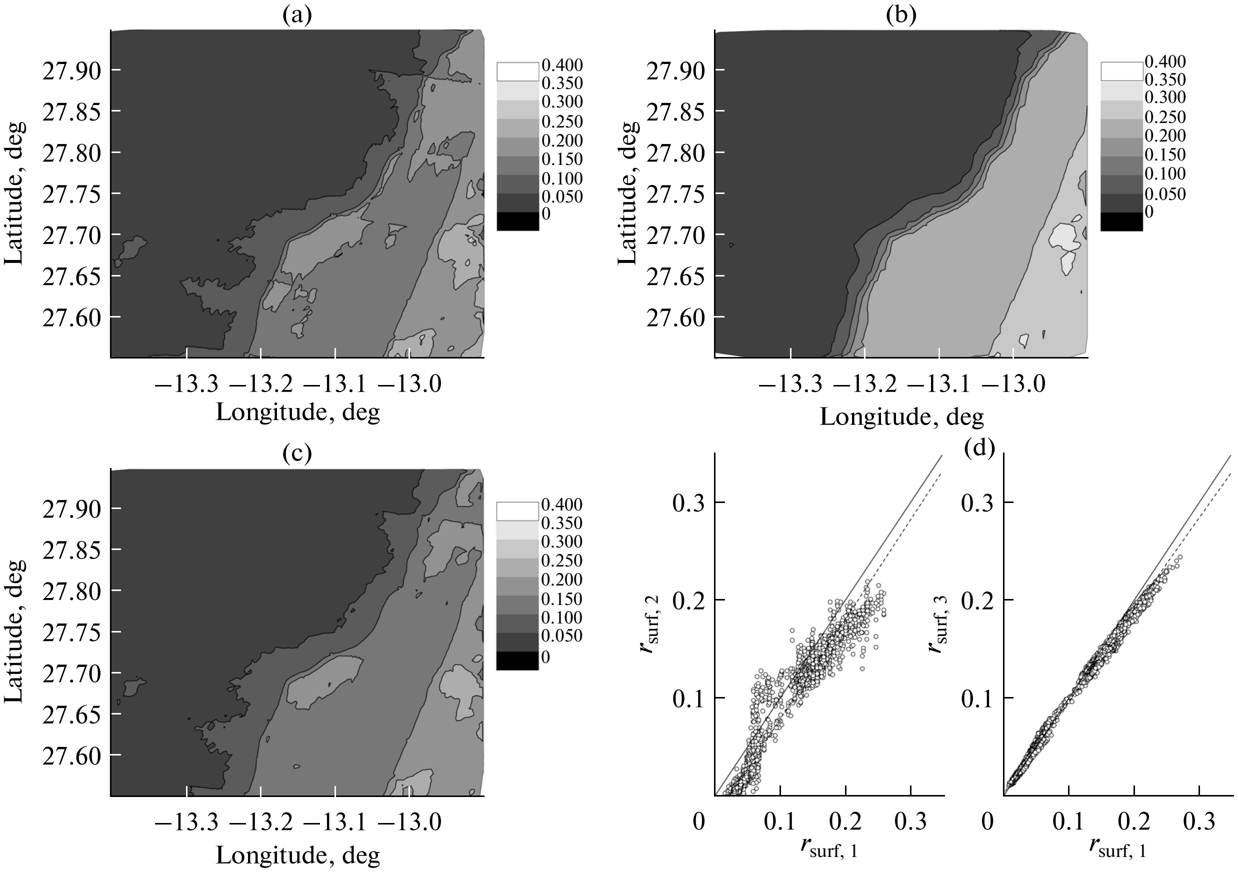

Fig. 4. (a) Reflection coefficients obtained by the basic algorithm for the Earth's surface area under consideration ($r_{\text{surf, 1}}$); (b) coefficients obtained by the MOD09 algorithm ($r_{\text{surf, 2}}$); (c) coefficients obtained by the homogeneity correction algorithm ($r_{\text{surf, 3}}$); and (d) comparison of values of the reflection coefficient obtained by the basic algorithm $r_{\text{surf, 1}}$ with values obtained by the MOD09 algorithm $r_{\text{surf, 2}}$ and homogeneity correction algorithm $r_{\text{surf, 3}}$.

coast of Africa with coordinates of 27.5–27.9° N, 13.4–12.9° W was chosen; the measurements were performed on August 19, 2011, at 11:25 a.m. This region was chosen due to the fact that about a half of it is occupied by desert territories; the second half, by a sea. As the initial data for the proposed algorithm and homogeneity correction algorithm, we used MOD02 and MOD04 data on the intensity distribution in the third channel of the MODIS device (0.47 μm) with a spatial resolution of 500 m and the AOD which was almost unchanged and equal to 0.307 in this case. The optical model of the atmosphere for the basic algorithm and homogeneity correction algorithm was chosen among continental tropical models of a cloudless sky. The model with $S_M =$ 24 km appeared to be the closest in the AOD. Results of calculations showed (Fig. 4) that the correlation coefficient for values obtained by the proposed algorithm and MOD09 algorithm equals 0.984 (Fig. 4d, left); the coefficient of correlation between values obtained by the proposed algorithm and those obtained by the homogeneity correction algorithm is 0.999 (Fig. 4d, right).

In addition, values obtained by the MOD09 algorithm are less than those obtained by the proposed algorithm by 0.023 on average. This can be connected with differences in the optical models applied in calculations. The comparison with the homogeneity algorithm shows that, in this case, one can use the homogeneity correction algorithm, which makes it possible to obtain a result with an additional error (the maximum difference in r_{surf} is 0.032) but requires much less time (by 6–10 times).

CONCLUSIONS

Thus, comparing results of using the proposed algorithm with calculation results of the MOD09 algorithm for a test area shows that results of the proposed algorithm are larger by 0.023 on average but the correlation coefficient is 0.984. The differences can be connected with differences in the optical model of the atmosphere. The comparison with the homogeneity correction algorithm shows that, in this case, one can use the homogeneity correction algorithm by virtue of a low turbidity of the atmosphere.

In the future, it is planned to choose an optimum (in the aspect of machine time consumption) method for solving systems (2) and (4), as well as to extrapolate the algorithm to situations with the presence of cloudiness.

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