Retrieval of the Optical Parameters of the Atmosphere from Satellite Radiative Observation

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Abstract – Data of remote multiangle measurements of reflected radiance are used for retrieval of the optical thickness, single scattering albedo and phase function parameter of cloudy and clear atmosphere. The method of perceptron neural network allows obtaining the surface albedo, optical thickness, single scattering albedo and phase function parameter from input values of multi-angle radiance and solar incident angle of clear pixels. All mentioned parameters were randomly varied on the base of statistical models of possible measured parameters variation. An analytical method of the retrieval is applied to remote observations of reflected radiance of cloudy pixels. The slight horizontal heterogeneity of cloud is approximately taken into account. The simultaneous retrieval of the optical thickness and single scattering albedo at every wavelength independently and without rough restrictions on parameters retrieved is the advantage comparing with earlier studies. The methodology of the asymmetry parameter retrieval is proposed.

Keywords: optical thickness, single scattering albedo, neuron network, perceptron

1. INTRODUCTION

Satellite observations are accomplished regularly and with using different instruments last decades. Thus big data arrays provide vast possibilities for inverse problem solution, particularly for retrieving atmospheric optical parameters from measuring values of the reflected shortwave solar radiation. Remote observation allows obtaining in global scale optical parameters averaged over pixels, which are necessary for calculation of any radiative characteristics (radiance, irradiance, radiative flux divergence) and application in radiative block of climate simulation. Just values obtained from observations are the adequate to real atmospheric parameters in contrast of the modeling results. Numerous precedent variants of the problem solution were based on significant restrictions put on the retrieved parameters.

These proposals are aimed to the retrieval of optical parameters of free and cloudy atmosphere and earth surface from satellite observation of solar reflected shortwave radiance. The numerical method of neuron perceptron net (nonlinear regression) is proposed for application to cloud free pixels and analytical method of inverse asymptotic formulas - to cloud pixels. Point out that the correct interpretation of radiation observation is based on the monochromatic theory of the radiative transfer and is possible just for spectral measurements data. The proposed methods of retrieval need multiangle measurements of the reflected radiance within narrow shortwave spectral intervals. Observations with the POLDER instrument from the board of ADEOS satellite satisfy our methods. Here we intend to use POLDER data, LEVEL 1.

The POLDER instrument (Deschamps et al., 1994; Bréon & CNES Project Team, 1997) provides observation of reflected intensity (radiance) in 8 spectral channels in the range 0.443 – 0.910 μm. For every pixel of the image values of the reflected intensity are available in several (till 14) viewing direction. Observations were accomplished regularly during 8 months 1996-97 and they covers all globe excludes polar night zones.

Values of atmospheric optical parameters (optical thickness, single scattering albedo and asymmetry parameter of the phase function for every pixel (cloud and clear) and ground albedo only for clear pixels are proposed to obtain for every spectral channel, calculate radiative characteristics (reflected and transmitted irradiance, radiative flux divergence. Because data are available in a global scale during 8 months, the results will be averaged over space and time for obtain optical and radiative models of the atmosphere.

2. PROBLEM STATEMENT

Satellite image consists from separate picture elements – pixels. During the primary processing of the satellite information they are divided to cloudy (the cloud amounts is one from the pixel characteristics) and cloud free or clear. While accomplishing the problem solution different methods are applied to processing cloudy and clear pixels.

2.1. Clear pixels processing

The method of perceptron neural network (Terekhov, 1998) that allows to obtain the ground albedo, total (aerosol plus molecular) optical thickness, single scattering albedo and phase function parameter from input values of multiangle radiance and solar incident angle. Atmospheric parameters are determined as average for atmospheric column. The calculation of solar radiance with using the MODTRAN-3 (Kneizis et al., 1996), code with taking into account multiple scattering is accomplished for neural network learning. A-priory atmospheric characteristics are input as temperature and absorbing gases profiles. All mentioned parameters were randomly varied on the base of statistical models of possible measured parameters variation (Timofeyev, Polyakov, 2001; Timofeyev, 1998). Since input information flow is a random one (because of measurement errors, perturbation ignored and so forth) a risk estimation task appears, that is a task of confidence intervals estimation for output parameters. Apart from it in the project it is implied to carry out analysis of the neural network structure to look after optimal interactions between perceptrons.

The methodology elaborated allows operative determining optical characteristics clear atmosphere. Further interpretation of these results gives the possibility to extract the information about total contents of atmospheric aerosols and absorbing gases in the atmosphere and create models of the clear sky.

2.2. Cloudy pixels processing

The inverse problem solution in case of cloudy pixels is proposed to obtain on the base of analytical method elaborated by (Melnikova et al., 2000a; Melnikova and Nakajima, 2000; Melnikova and Vasilyev, 2004) where the detailed derivations of formulas, error analysis and applications are shown. The analytical methodology is based on the inverting the asymptotic formulas for optically thick turbid layer of the transfer theory. As the given inverse problem in its general formulation belongs to non-correct tasks in the work it is proposed to limit the restored parameter domain by space, inside of which the transformation is one-value solvable and continuous.

Here we present the formulas that will be applied to remote observations of reflected radiance in case of cloudy pixel. Processing the satellite image with pixel size 6x6 km will be accomplished within the ranges of the proposals. The model of horizontally infinite layer is considered. The slight horizontal heterogeneity is approximately taken into account following to (Melnikova et al., 2000b).

Let the reflected radiance ρ_1 and ρ_2 be measured within two nadir viewing angles arccosμ_1 and arccosμ_2. Introduce the parameters $s=\sqrt{(1-\omega_0)/(3-3g)}$, defining the absorption of the radiation in the atmosphere and scaled optical thickness $\tau'=3\tau_0(1-g)$, defining the scattering of the radiation., then the following formulas containing only the measured values of two-direction radiance and functions of solar and view angles are used for retrieval these parameters:

$$s^2=\frac{[\rho_0(\varphi,\mu_1\mu_0)-\rho_1]K_0(\mu_2)-[\rho_0(\varphi,\mu_{2,}\mu_0)-\rho_2]K_0(\mu_1)}{[\rho_0(\varphi,\mu_{2,}\mu_0)-\rho_2]K_0(\mu_1)\left(\frac{K_2(\mu_1)}{K_0(\mu_1)}-\frac{K_2(\mu_2)}{K_0(\mu_2)}\right)-\frac{0.955a_2(\mu_0)K_0(\mu_1)K_0(\mu_2)}{q'(1+g)}[\mu_1-\mu_2]},$$

$$\tau'=(2s)^{-1}\ln\left\{\frac{m\bar{l}K(\mu_i)K(\mu_0)}{\rho_\infty(\varphi,\mu_i,\mu_0)-\rho_1}+l\bar{l}\right\}\quad, \qquad (1)$$

where φ is the azimuth viewing angle relatively the Sun direction. The escape function $K_0(\mu)$ and plane albedo $a_2(\mu)$ are calculated with using known formulas for known viewing and solar angles; δ=1,428 and the value g is the asymmetry parameter of the phase function. The approach for estimating the last parameter is presented in the following section. The 6 azimuth harmonics of reflection function $\rho_0(\varphi,\mu_1,\mu_0)$ are taken into account according to (Melnikova et al., 2000b). The simple approximation of the cloud top boarder heterogeneity is used. The clouds, projecting upper the cloud top plane causes the increase of diffuse radiation in the incident flux. It is essential for calculation of radiative characteristics, which depends on lighting conditions. Escape and reflection functions describe this dependence for reflected radiance and local albedo of semi-infinite medium – for irradiance. Thus the functions depending on solar incident angle is to replace by their modifications. If the optical thickness exceeds 100 the corresponding formula for obtaining the parameters s is the following (Melnikova and Vasilyev, 2004):

$$s=\frac{2K_0(\mu)K_0(\mu_0)-\sqrt{4\left[K_0(\mu_0)K_0(\mu)\right]^2-\frac{a_2(\mu_0)a_2(\mu)}{12q'}\left[\rho_0(\mu,\mu_0,\varphi)-\rho\right]}}{\frac{a_2(\mu_0)a_2(\mu)}{12q'}} \qquad (2)$$

2.3. Processing of satellite data

The following algorithm is elaborated for cloud pixels processing.

1. Firstly functions depending on solar and viewing and azimuth angles are calculated. The asymmetry parameter is taken corresponding to scattering theory calculation (version 1) or retrieved using the methodology described in the following section
2. Then the optical thickness of every pixel is obtained with simple formula assuming conservative scattering for all available view directions.

$$3(1-g)\tau_0=\frac{4K_0(\mu_0)K_0(\mu)}{\rho_0(\mu,\mu_0)-\rho}-\left(6q'+\frac{4A}{1-A}\right)\ , \qquad (3)$$

Deviations between obtained values may be taken as a measure of the cloud top distinction from the plane.

3. The special parameter is obtained, which takes into account the shadow effect (heterogeneity of the cloud top).
4. Then single scattering albedo and optical thickness (with the true absorption assuming) are obtained for pairs of viewing directions with equal optical thickness.
5. After that the averaging of values obtained and relative error evaluation is accomplished for all viewing directions of every pixel.
6. The procedure is repeated for all wavelengths and pixels independently.
7. The results obtained are prepared for mapping and presented in geographical coordinates using GRADS editor.
8. Relative errors are calculated as deviation from the mean value and using formulas for errors for every pixel and every wavelength. In the high latitudes errors increase to

the image edge, that called by unfavorable geometry of measurement.

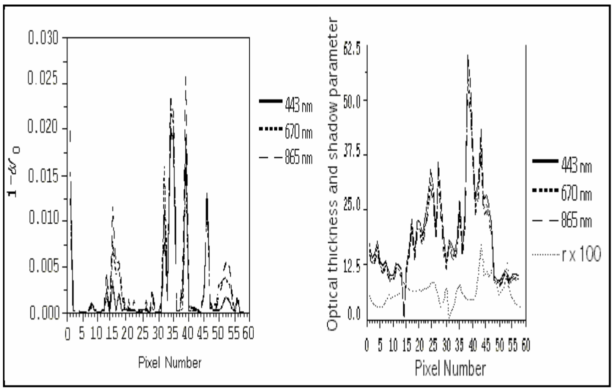

Figure 1. Cloud optical parameters versus pixel numbers: a) – the single scattering co-albedo ($1-\omega_0$), and b) – the optical thickness τ_0 (solid line) and shadow parameter r x 10^2 (dashed line) for three wavelength channels 443 nm – black line; 670 nm – red line; 865 nm – blue line; Latitude 58.75°N and longitude 23°W–75°;

Fig. 1 demonstrates the results of cloud pixels processing applying to POLDER data, LEVEL 2 for 24 June 1996 for band of averaged pixels with the size 60x60 km. Here we intend to process images consisting from pixels with the size 5x5 km without averaging. Thus the results of the study will show how the pixel size impact on exactness of the retrieval and will demonstrate the measure of the heterogeneity of real clouds

2.4. The inverse problem of retrieving the phase function for cloud pixels from satellite observation.

The approach proposed in (Konovalov, 1997) is applied for retrieval the phase function parameter g in the case of cloudy pixel. The following assumptions are taken for the problem solution.

1. The angular scheme of the experimental data is indicated with points on the unit sphere.
2. Pixel size is to be enough big optically for possibility to consider the pixel as a diffusion domain.
3. The number of solar and viewing nadir angles would be enough.
4. It is desirable the values of solar and viewing nadir angles cover the equatorial part of the unit sphere enough compact.

It is clear that there is not ideal geometry of satellite observation for retrieval. Thus the operation of the interpolation and approximation are necessary and additional errors appear.

Thus the problem of the retrieval of the phase function is reduced to two tasks:

– The interpolation or extrapolation of the experimental results to needed points on the unit sphere.
– The retrieval of the phase function according to formula (4).

Task 1. The choice of base points on the unit angular sphere.

It is necessary to choose solar and viewing angles correctly for they would be as close as possible to 90°. It is enough to take two points for viewing angle ϑ_1 and ϑ_2 and one point for solar angle ϑ_0 for application of the algorithm of the phase function retrieval.

Task 2. The interpolation of experimental results over necessary set of points corresponding to viewing or solar angles

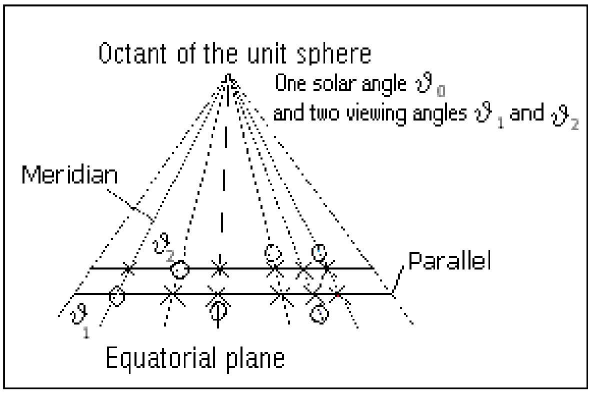

Figure 2. The octant of the unit sphere

For fixed solar angle ϑ_0 two latitudinal planes are drawn through viewing angles ϑ_1 and ϑ_2. Two parallels of the azimuthal development are obtained on the unit sphere surface, as it demonstrated in Fig. 2. Circles correspond to experimental data. Meridianal lines are drawn through experimental points corresponded azimuthal viewing angles. Crosses indicate crossing meridians and parallels. Point out that in the Fig 2 two experimental points ϑ_1 and ϑ_2 are points of crossing. But it is not obligatory, because parallels may be drawn arbitrary, basing on some other assumptions e.g. special algorithms of the interpolation. It is important that these parallels pass close to the equatorial part of the unit sphere.

Our first task is to interpolation values of the radiance corresponding to experimental. Circles to values corresponding crosses. After interpolation we obtain the radiance arrays developed over azimuth and needed for calculation of the phase function. Certainly this operation adds an uncertainty, which is the less one, the more number of blue points is and the more compact they cover the environs of these two parallels.

Finally we obtain two radiance dependence of azimuthal angle for fixed value of solar nadir angle ϑ_0 and two viewing angles ϑ_1 and ϑ_2: $I(\vartheta_0,\vartheta_1,\varphi_j)$ and $I(\vartheta_0,\vartheta_2,\varphi_j)$.

These functions of φ_j will be used for phase function retrieval according to the formula, derived by (Konovalov, 1997).

During the project accomplishing the methodology version providing the best exactness of the retrieval will be chosen

Task 3. Retrieval of the phase function

For the retrieval of the phase function the formula derived in [12 is applied]:

$$x(\cos\varphi) = 4\frac{\left[b_2(\mu_0+\mu_1)I_1 - b_1(\mu_0+\mu_2)I_2\right]}{\omega_0\mu_0F_0(b_2-b_1)} \qquad (4)$$

where value b_i defines the expression:

$$b_i = b(\mu_i,\mu_0) = \mu_i \ln\mu_i + \mu_0 \ln\mu_0 \,, \qquad (5)$$

$$\cos\gamma = \mu_1\mu_0 + \sqrt{(1-\mu_1)^2(1-\mu_0)^2}\cos\varphi \,;$$

I_i is the measured reflected radiance within the viewing angle ϑ_1 =arccosμ_I and azimuthal viewing angle φ is the same for both observations I_i.

It is easy to obtain the asymmetry parameter g taking into account that the Henyey-Greenstein formula is the following:

$$x(\gamma) = \frac{1-g^2}{\left(1+g^2-2g\cos\gamma\right)^{3/2}} \,. \qquad (6)$$

The resulting value of the asymmetry parameter g will be substituted to the algorithm of the processing data for cloudy pixels.

CONCLUSIONS

Big volume of satellite data different kind provides great possibilities for obtaining information about the Environment including atmospheric parameters. Observation within short wavelength range gives possibilities to retrieve optical parameters of the atmosphere. There are many results different quality. The best ones base on rigorous method of inverse problem solution. But all methods need many restrictions on the parameters retrieved (absence of the spectral dependence of the optical thickness, absence of the light absorption within shortwave ranges, and others) and additional assumptions (e.g. infinitely optically thick cloud layer, conservative scattering), which don't allow obtaining the result adequate to the nature reality, but adjusting desired values to known models. But in case of true absorption in clouds or optical thickness less than 100 the large errors in parameters obtained are inevitable.

There were not results in the field of phase function parameter to retrieve from satellite observation also and the asymmetry parameter g has been chosen from modeling calculation. The neuron net method has not yet applied to the retrieval optical parameters of the atmosphere, thus our attempts to use this method is new one.

The analytical method of the optical parameters retrieval in case of cloudy atmosphere has a significant improvement because it demands less restriction on desired parameters and assumptions than numerical methods.

Our study is aimed to retrieval of the atmospheric optical parameters from satellite data. There is no special restrictions excluding the evident one – the parameters obtained are to be non-negative). Proposed approaches are new, (or they have not applied earlier either applied by authors of the proposals for small data sets). Authors have elaborated two of these methods. Parameters are obtained for all available spectral channels independently. The simultaneous retrieval of two parameters of cloudy atmosphere (may be we will succeed 3 parameters) at every wavelength independently is the advantage comparing with earlier studies.

. The problem of big arrays of satellite data processing in the real time is of great importance now. Proposed approaches for atmospheric optical parameters retrieval connect with minimum arithmetic procedure, therefore they provide very fast data processing. For example 100 cloudy pixel processing takes 1 sec. Thus it may be accomplished in real time operation.

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