CORRECTION OF THE OPTICAL MODEL OF THE ATMOSPHERE IN SITU DURING THERMAL SENSING FROM SPACE

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We propose a method for the correction of the optical model of the atmosphere in the problem of determining the temperature profile $T(\xi)$ from the results of reconstruction of the vertical profile of the nonselective component of the optical depth of the atmosphere. The reconstruct ion is made by means of measurements of the outgoing IR radiation. Examples are given of the solution of model problems.

INTRODUCTION

The spatial-temporal variability of optical conditions in the atmosphere is the main factor hindering the Interpretation of the data of remote thermal sensing of the Earth from space. Existing methods of inversion of satellite data[1] permit the reconstruction of vertical temperature profiles $T(\xi)$ of the atmosphere. However, variations of the optically active components of the atmosphere (water vapor, carbonic dioxide, etc.) determine to a significant degree the variations of the radiation fields being measured from space of the outgoing IR radiation for a given thermal state of the system "atmosphere-surface". Finally, the accuracy of the inversion of satellite data is determined by the correct registration of the optical condition of the atmosphere in situ, i.e., the atmospheric transmission in the given spectral regions $\Delta\lambda_i$ of the remote sensing systems at the time of the satellite measurements.

Strict requirements are placed on the knowledge of the transmission functions of the atmosphere in the channels $\Delta\lambda_i$ of systems of remote thermal sensing of the atmosphere for the purpose of restoration of vertical profiles $T(\xi)$[2,3]. Transmission functions which are precalculated for the given regions and seasons are commonly used. But even the most precise direct linear calculations of these functions do not ensure the restoration of $T(\xi)$ with the required accuracy since the entire variety of optical states of the atmosphere cannot be covered by transmission calculations computed on the basis of a limit number of models. To correct the calculated transmission functions Haughton[2] suggests to make use of measurements of the attenuation of IR radiation by the atmosphere made by stratospheric balloons or sondes flying under the satellites. To refine the transmission functions for the given region Pokrovskii and Timofeev[4] and Denisovich and Pokrovskii[5] suggest the use of aerological sensing data on the temperature profile $T(\xi)$ from one subsatellite point. Pokrovskii and Belyavskii[6] have used subsatellite reference sensing data for "latitude and zone adjustment". The correction of the optical model of the atmosphere in Ref. 6 is achieved by minimizing the deviation of the difference the measured intensities $\tilde{I}_i$ and the calculated (on the basis of radiosonde data) intensities I_i from the difference of the intensities $\tilde{I}_i$ and $\bar{I}_i$, where the intensities $\bar{I}_i$ are calculated for the mean-climatic model of the atmosphere. Such a correction method can lead to the loss of information about the sought-for profile $T(\xi)$ contained in each satellite measurement included in each satellite measurement. The content of information about both a vertical temperature profile $T(\xi)$ and an optical atmosphere state in the spectral measurements of outgoing IR radiation requires the method which is physically proved to determine the sought parameters of the "atmospheric-surface" system using the direct satellite measurements in situ. In this case the atmospheric transmission functions corrected by the under-satellite aerological data corresponded to the optical atmospheric state when the satellite measurements are not provided with such data. Therefore the under-satellite reference sensing is not required. With the set spectral distribution of aerosol attenuation in the two spectral regions 4.3 μm and 15 μm the attempt of vertical profile $T(\xi)$ restoration jointly with the estimation aerosol attenuation using the multichannel measurements of $\tilde{I}_i$ were undertaken[7]. The satisfactory result of the solution of the modeled problem is explained by "measurements" in the transparence windows (3.7 μm and 11 μm) and in the spectral regions mentioned above with the same aerosol attenuation a priori known. The variability of spectral dependence of aerosol attenuation, including the neighbor regions of the spectrum (11 μm and 15 μm), makes impossible to use the "complex" method[7]. For interpretation of the real satellite measurements.

The information content in the spectral measurements of the outgoing IR radiation on both the vertical temperature profile $T(\xi)$ and the optical state of the atmosphere suggests a physically based method of determining the sought-for parameters of the system "atmosphere-surface" directly from the satellite measurements in situ. In this case the question of the identity of the transmission functions corrected by subsatellite aerological data with the optical state of the atmosphere at the time of the satellite measurements, which are not provided with such data, is obviated since subsatellite reference sensing is not required. With the spectral dependence of the aerosol attenuation in the two spectral regions 4.3 and 15 μm prescribed in Ref. 7, we undertook an effort to recover the vertical profile $T(\xi)$ along with an estimate of the aerosol attenuation from multichannel measurements $\tilde{I}_i$ in these two spectral regions. The satisfactory result of the solution of the model problem[7] can be explained by the use of "measurements" in the attenuation "windows" at 3.7 and 11 μm. The variability of the spectral dependence of the aerosol attenuation, including the neighboring spectral regions 11 and 15 μm, makes it impossible to use the "complex" method in the interpretation of actual satellite measurements.

We propose to correct the optical model of the atmosphere in the solution of the problem of thermal sensing, in this work by the use of a method for recovering the optical depth which does not make use of subsatellite aerological measurements.

DETERMINATION OF THE OPTICAL DEPTH

The problem of determining the profile of the optical depth $\tau_i(0, \xi)$ from satellite measurements of the outgoing IR radiation $\tilde{I}_i(\theta_j)$ is formulated in the following way:

$$\min_{\Phi(\tau)\le 1} \Phi(\tau), \qquad \tau_i(0,\xi) \in \Omega \tag{1}$$

Here the discrepancy $\Phi(\tau)$ is given by

$$\Phi(\tau) = \frac{1}{N\,M} \sum_{i=1}^{N} \sum_{j=1}^{M} [\tilde{I}_i(\theta_j) - I_i(\theta_j)]^2/\sigma^2_{ij} \tag{2}$$

where σ^2_{ij} is the variance of measurements errors, $\tilde{I}_i(\theta_j)$ are the satellite measurements, and $I_i(\theta_j)$ are the intensities of the outgoing IR radiation in the direction of the zenith angle θ_j in the i-spectral channel (with the spectral characteristic $\varphi_i(\lambda)$ with halfwidth $\Delta\lambda_i$), calculated by minimization of $\Phi(\tau)$ and are functions of the unknowns $\tau_i(0, \xi)$:

$$I_i(\theta_j) = \varepsilon_i(\psi_j)\, B(T_0)\, P_i(0,1,\theta_j) - \int_0^1 B_i[T(\xi)] \frac{\partial P_i(0,\xi,\theta_j)}{\partial \xi}\, d\xi \tag{3}$$

The solution of the transfer equation for longwave radiation in the form (2) is used for convenience in the calculations. Here $\varepsilon_i(\psi_j)$ are the effective values of the emissivity of the underlying surface in the direction $\psi_j(\psi_j = \theta_j$, not taking into account the curvature of the Earth), $B_i[T(\xi)]$ is the Plank function ($B_i[T(\xi)] = B_{\lambda_i}[T(\xi)]$ for λ_i from $\Delta\lambda_i$), and $\xi = p/p_0$ is the height in relative pressure units (p_0 is the normal pressure at surface level). The transmission function $P_i(0, \xi, \theta_j)$ of the atmospheric layer $(0, \xi)$ in the direction of θ_j is represented in the form

$$P_i(0,\xi,\theta_j) = P^s_i(0,\xi,\theta_j) \times P^n_i(0,\xi,\theta_j) \tag{4}$$

as the product of the selective component $P^s_i(0, \xi, \theta_j)$, calculated for the given model of atmospheric transmission of the IR radiation in the absorption lines of the gaseous components of the atmosphere (taking into account $\varphi_i(\lambda)$), and the nonselective component of the transmission function[8] $P_i(0, \xi, \theta_j) = \exp\{\eta - m_{jj}\, \tau_l(0, \xi)\}$ where $m_j = \sec\theta_j$ accounts for the intervening air mass. The unknown optical depth $\tau_l(0, \xi)$ characterizes the absorption of IR radiation in the continuum and by aerosol, and also includes within itself the possible errors of calculation of the quantity $P^s_i(0, \xi, \theta_j)$ due to the noncorrespondence of the real atmosphere during the satellite measurements with the mean climatic model.

An example of the calculation of the selective absorption of the atmosphere (the tropical model) in the spectral region 10–15 μm (Ref. 8) is given in Fig. 1. Here are also shown the results of a calculation with the same resolution (4 cm^{-1}) of the absorption of the single-component (water vapor) atmosphere, and also the spectral characteristics $\varphi_i(\lambda)$ of the spectral channels of the nonscanning (measurements of nadir) IR radiometer used onboard the satellite "Kosmos-1151", data from which are used below to recover the temperature profile of the atmosphere $T(\xi)$.

The use of angular measurements to determine $\tau_i(0, \xi)$ by minimizing the discrepancy $\Phi(\tau)$ (given by Eq. (2)) is not obligatory since their presence, by virtue of the smoothing effect of the operator of the problem, permits a decrease of the influence of the random errors of measurement σ_{ij}. When the spectral dependence $\tau_i(0, \xi)$ is prescribed, for example in parametric form $\tau_i(0, \xi) = a_i\tau_{\lambda 0}(0, \xi)$ ($\tau_\lambda(0, \xi)$ is the optical depth of the atmosphere at some reference wavelength λ_0), the use of multichannel measurement in the statement of the problem (1) is justified. Figure 1 also shows the spectral dependence of the absorption of the IR radiation by water vapor in the continuum $a_i^{H_2O}$ from measurements[9] in the transparency microwindows, and the possible spectral dependence of the aerosol absorption α_i^{aer} from data given in Ref. 10 ($\alpha_i = 1$ for $\lambda_i = 11$ μm). The question of the relation between the continuum absorption of water vapor and the aerosol extinction still remains unsolved. This is evidently due to the difficulty of calculations of the continuum and the aerosol absorption as well as to the strong variability of the aerosol, also in the spectral sense (see, e.g., Refs. 10 and 11). The assumption of the nonselectivity of $\tau_i(0,\ \xi)$ in the interval $\Delta\lambda_i$ is an important approximation in the solution of problem (1) using multispectral measurements $\tilde{I}_i(\theta_i)$. As previously stated a parameterization of the form of $\tau_i(0,\ \xi) = \alpha_I\ \tau_{\lambda 0}(0,\ \xi)$ is possible for the spectral dependence of the optical depth on λ_i.

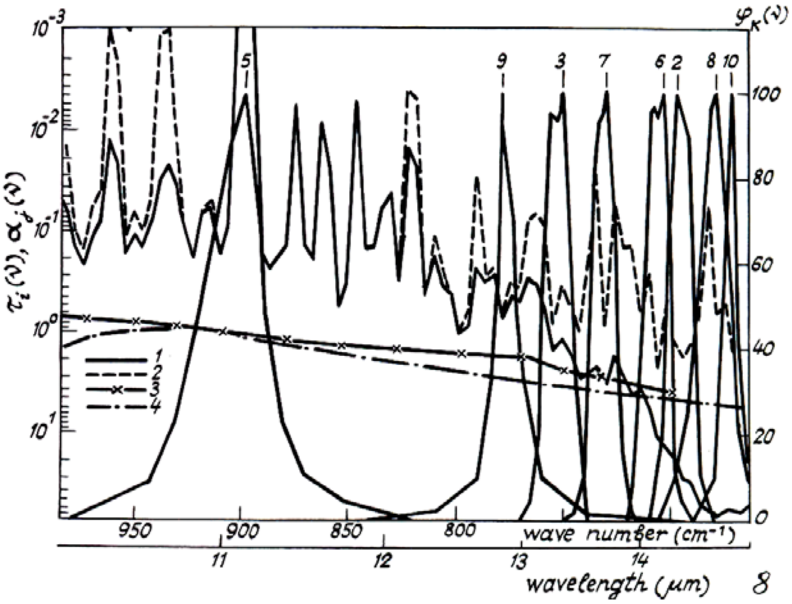

FIG. 1. Curve 1 is calculated[9] *selective absorption of IR radiation by a three-component (*H_2O, CO_2, O_3*) atmosphere (tropical model resolution 4* cm^{-1}*); curve 2 is the same for the one-component atmosphere (*H_2O*); curve 3 is the spectral dependence* $\alpha_\lambda^{H_2O}$ *of the absorption due to water vapor in the continuum*[9]*; curve 4 is the same for the aerosol* α_λ^{aer} *(Ref. 10). The spectral characteristics* $\varphi_i(\lambda)$ *of the channels of the IR radiometer onboard the satellite "Kosmos-1151", used in the restoration of* $T(\xi)$*, are also shown.*

The search for the nonselective component of the optical depth in the formulation of problem (1) leads to a set of monotonic and bounded functions Ω, which ensures a regularized solution of the inverse problem. It is also possible to search for the solution $\tau_i\ (0,\xi)$ by minimizing the discrepancy $\Phi(\tau)$ over other, possibly rather exotic subsets ω of Ω. From our efforts to solve problem (1), we have made the observation that it is impossible to satisfactorily determine the optical depth $\tau_i(0,\ \xi)$ from measurements in the CO_2 absorption band at 15 μm. This fact is explained by the smoothing effect of the operator $W_i(\xi)$ (the weight function) on the "true" profile $\tilde{\tau}_i(0,\ \xi)$, in the formation of the intensity $I_i(\theta_j)$. However, the proposed method permits the confident recovery of $\tau_i(0,\ \xi)$ from angular measurements of $I_i(\theta_j)$ in the transparency "window". In this case the results of the restoration of $\tau_i(0,\ \xi)$ dependent weakly on the form of the profile of $T(\xi)$ used in the solution of problem (1). In the search for $\tau_i(0,\ \xi)$ one can use profiles $T_s(\xi)$ recovered by the method of statistic regularization with respect to nadir measurements $\tilde{I}_i\ (0°)$ in the CO_2 band at 15 μm with kernels of Eq. (3) corresponding to the estimates of selective absorption for the mean-climatic model atmospheric may be applied. The solution of problem (1) on the basis of measurements $\tilde{I}_i(\theta_j)$ in the transparency "window" does not reliably reveal the vertical structure of the true profile $\tilde{\tau}_i(0,\xi)$; however, stability of the solution $\tau_i(0.1)$ is characteristic when the input parameter T_0 is prescribed with an error of ~ 1.5–2°C. The reliable determination of $\tau_i(0.1)$ on the basis of measurements in the transparency "window" is explained by the specific form (δ-function shape) of the kernel of the integral equation (3) at the surface level and by the form of the weight functions $W_i(\xi)$ in this region of the spectrum.

Figure 2 shows examples of the vertical profile $\tau_i(0,\ \xi)$ restored by minimization of $\Phi(\tau)$ Eq. (1). The initial profile (curve 1) was modeled by an exponential height distribution with superimposed aerosol absorption at a height $h \sim 6$ km i.e., it had the form $\tilde{\tau}\ (0,\xi) = 0.2\ \exp\{-0.125\ h(\xi)\} + 0.1\ \delta\ (h,\ 6)$, where $\delta\ (h,\ 6) = 0$ for $h > 6$ km and $\delta\ (h,\ 6) = 1$ for $h \le 6$ km. The solution of the complete problem (1) from "measurements" $\tilde{I}_5(\theta_j)$ ($\varepsilon_i(\varphi_i) = 1$) of the fifth channel ($\lambda_5 = 10.99\ \mu$m) of the scanning IR radiometer onboard the satellite "Kosmos-1151" (Ref. 8) ($\theta_1 = 48°$, $\theta_2 = 54°$) gives a smoothed profile $\tilde{\tau}_5(0,\xi)$ (curve 2).

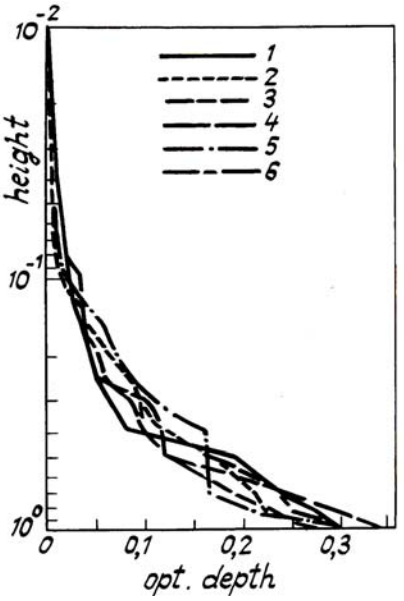

FIG. 2. Restoration of the profile of the optical depth: 1) the initial profile; 2) the solution of the complete problem from the "measurements" $\tilde{I}_5(\theta_j)$ (λ = *10.99 μm,* $\theta_1 = 48°$, $\theta_2 = 54°$*); 3) similarly as for the curve 2, but from the "measurements"* $\tilde{I}_5(\theta_j)$ *and* and $\tilde{I}_6(\theta_j)$ (λ_6 = *14.14 μm,* $\tilde{a}_5 = \tilde{a}_6 = a_5 = a_6$*); 4) similarly as for curve 3, but with* $\tilde{a}_1$ *and* a_1 *from Ref. 9; 5) similarly as for curve 3, but with* $\tilde{a}_1$ *from Ref. 9,* $a_5 = \tilde{a}_5$ *and* $a_6 = \tilde{a}_6 / 2$*; 6) similarly as in curve 4 (the incomplete problem).*

The addition of "measurements" $\tilde{I}_6(\theta_j)$ of the sixth channel (λ_6 = 14.14 μm) in the search for $\tau_{\lambda_0}(0, \xi)$ provides a better determination of the vertical structure of $\tilde{\tau}_{\lambda_0}(0, \xi)$. Here different values of the ratio $\tilde{a}_6$ of the optical depth $\tilde{\tau}_6(0, \xi)$ to the reference depth $\tilde{\tau}_5(0, \xi)$ ($\lambda_0 = \lambda_5$ = 11 μm) were considered. Curve 3 illustrates the solution of the ($\tilde{a}_6 = \tilde{a}_5 = 1$), while curve 4 illustrates the solution of the complete problem for the spectral, dependence of $\tilde{a}_1$ based on the measurements in Ref. 9. In both of these cases the search for $\tau_5(0, \xi)$ (for $\lambda_0 = \lambda_5$ = 11 μm) was performed with a priori prescribed values of a_i which were the same as "true" values $\tilde{a}_i$ for which the initial profiles $\tilde{\tau}_5(0, \xi)$ and $\tilde{\tau}_6(0, \xi)$ ($\tilde{a}_6 = a_6$, $\tilde{a}_5 = a_5 = 1$) were modeled in cases 3 and 4. Making the prescriptions $a_6 = a_5 = 1$ in the search for $\tau_5(0, \xi)$ for case 4 ($\tilde{a}_6$ from Ref. 9), there is no convergence in the minimization of $\Phi(\tau)$ for measurement errors σ_{ij} corresponding to the characteristics of the IR radiometer onboard the satellite "Kosmos-1151". However, the *a priori* assignment of other values of the parameter a_6, which also has an effect on the modeled spectral dependence $\tau_5(0, \xi)$, $\tau_6(0, \xi)$ allows one to recover $\tau_5(0, \xi)$ (curve 5, $a_5 = \tilde{a}_5$, $a_6 = \tilde{a}_6 / 2$). In other words, for some statement of the problem (1) it is possible to estimate the spectral dependence of $\tilde{a}_i$ of the nonselective component of the optical depth of the atmosphere from multispectral measurements I_i for given measurement errors σ_{ij}.

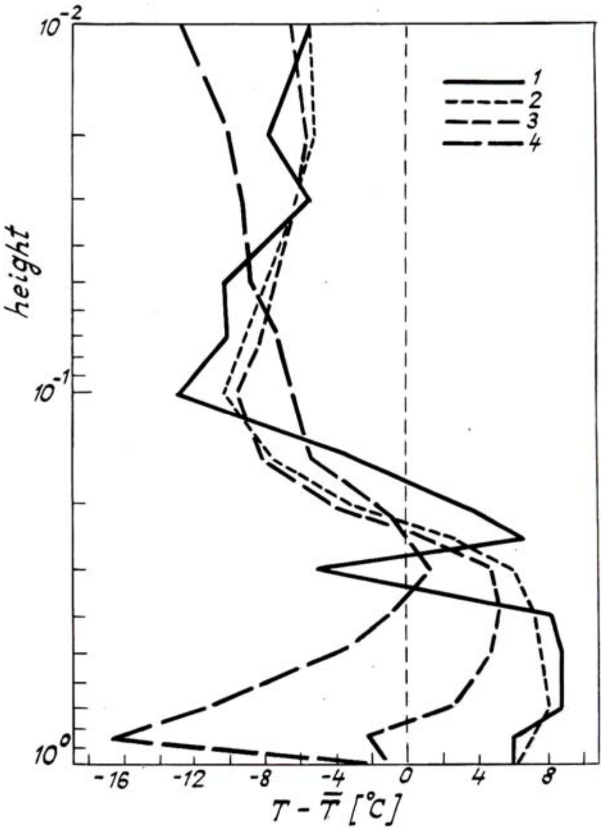

FIG. 3. Restoration *of the temperature profile T(ξ) (deviation from the mean-climatic model:* $t(\xi) = \bar{T}(\xi) - T(\xi)$ *without correcting for the optical model of the atmosphere: 1) initial profile, 2) restoration with unperturbed kernels, 3) restoration with the addition of* $\tilde{\tau}_i(0, \xi)$ *in the form of curve 1, Fig. 2 (* $\tilde{a}_i = 1$ *); 4) similarly as for curve 3, but with* $\tilde{a}_i$ *as given in Ref. 9.*

RESTORATION OF THE TEMPERATURE PROFILE

Using the results of the determination of the optical depth by the proposed method, it is logical to consider the possibility of the correction of the optical model of the atmosphere in the problem of thermal sensing of the atmosphere. Examples of the restoration of the vertical profile of the temperature of the temperature of the atmosphere $T(\xi)$ by the statistical regularization method with an inexact assignment of the kernels of Eq. (3) are shown in Fig. 3. Here and below we consider solutions of the incomplete problem, i.e., the measurements $\tilde{I}_i(\theta_j)$, calculated from Eq. (3) with the ”true” $\tilde{\tau}_i(0, \xi)$ and $\tilde{T}(\xi)$, were burdened by a random error of the measurements σ_{ij}. The level of the errors σ_{ij} and the set of spectral channels correspond to the characteristics of the IR radiometer onboard the satellite ”Kosmos-1151” ($\varphi_i(\lambda_0)$, which was used to recover the $T(\xi)$ channels, see Fig. 1).

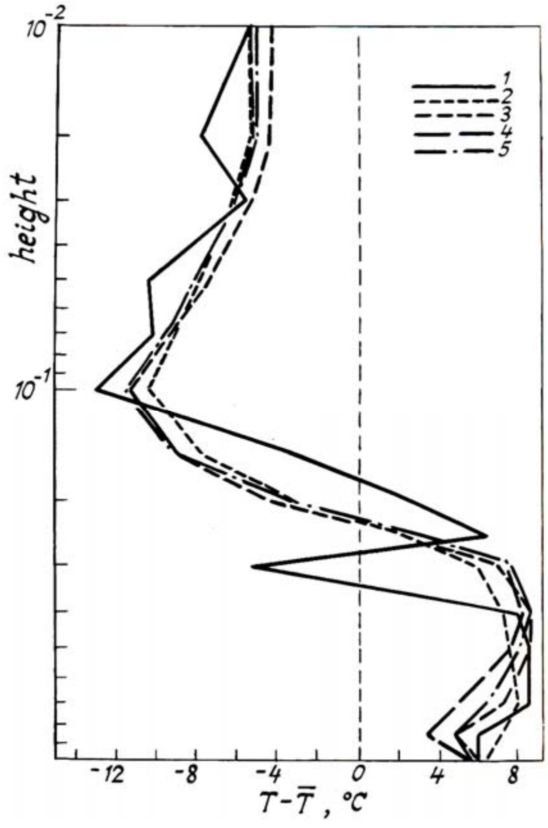

FIG. 4. Restoration of the temperature profile t(ξ) with correction from the results of the determination of τ_i*(0, ξ): curves 1 and 2 are the same as in Fig. 3, curve 3 is the restoration with the determination of* τ_i*(0, ξ) from the ”measurements”.* $\tilde{I}_5(\theta_j)$ *and* $\tilde{I}_6(\theta_j)$ *(* $\tilde{\alpha}_i = 1$, τ_i*(0, ξ) of the form of curve 1 in Fig. 2 (*$\alpha_i = 1$*)), curve 4 similarly as for curve 3, but with* $\tilde{\alpha}_i$ *and* α_I *taken from Ref. 9, curve 5 — similarly as for curve 4, but with* $\alpha_i = \tilde{\alpha}_i / 2$ *(* $\alpha_\lambda = \tilde{\alpha}_\lambda = 1$, *λ = 11 μm).*

The profile $T_s(\xi)$ (curve 2 in Fig. 3) illustrates the ability of the statistical regularization method with exact assignment of the kernels of Eq. (3) (see Ref. 1) for such errors σ_{ij} of the ”measurements” $\tilde{I}_i(0°)$. Restoration of the profile $T_s(\xi)$ from the intensities $\tilde{I}_i(0°)$ formed by the addition of the nonselective component $\tilde{\tau}_i(0, \xi)$ to the selective absorption, with kernels corresponding to the estimates of the selective absorption $P_i^s(0, \xi, \theta_j)$, leads to large errors. In the case when the values $\tilde{\tau}_i(0, \xi)$ are of the form of curve 1 in Fig. 2 and are identical for all the spectral channels ($\tilde{\alpha}_i = 1$), the errors in the determination of the profile $\tilde{T}(\xi)$ (curve 1 in Fig. 3) reach 8–10°C (curve 3). For $\tilde{\tau}_i(0, \xi)$ with the spectral dependence of $\tilde{\alpha}_i$ given in Ref. 9, these errors reach 20°C (curve 4). Depending on the form both of $\tilde{\tau}_i(0, \xi)$ and of the ”true” profile $\tilde{T}(\xi)$, the errors in the determination of $T_s(\xi)$ using the calculations of $P_i^s(0, \xi, \theta_j)$ corresponding to the mean-climatic model of the atmosphere can reach even higher levels.

The accuracy of determination of the vertical structure $T_s(\xi)$ depends on the ratio of the unknown nonselective component $\tilde{\tau}_i(0, \xi)$ to the magnitude of the selective absorption (for the chosen spectral channels $\Delta\lambda_i$). For neutral spectral dependence $\tilde{\tau}_i(0, \xi)$ ($\tilde{\alpha}_i = 1$), $T_s(\xi)$ is poorly determined only in the lower layers of the atmosphere (curve 3) since the values $\tilde{\tau}_i(0, \xi)$ in this .case are comparable with the selective absorption in the channels at the edge of the CO_2 band at 15 μm, the intensities of the outgoing IR radiation in which are determined by the atmospheric radiation in these layers. For the spectral dependence $\tilde{\tau}_i(0, \xi)$ given in Ref. 9, taking into account the possible correction of the calculated values of $P_i^s(0, \xi, \theta_j)$ which are used to recover $T_s(\xi)$ is also important and for the same reason in the upper layers of the atmosphere.

The solution of problem (1) enables one to correct the kernels of Eq. (3) and to improve the determination of the vertical profile $\tau_i(\xi)$. The result of the restoration of the profile $\tau_i(0, \xi)$ with the corresponding correction of $P_i(0, \xi, \theta_j)$ according to Eq. (4) enables one to determine the profile $T_s(\xi)$ (curve 3 in Fig. 4) almost with the same accuracy as for the exact assignment of the kernels of Eq. (3). Using a priori knowledge of the spectral dependence of $\tilde{\tau}_i(0, \xi)$ ($\alpha_i = \tilde{\alpha}_i$), the correction of the optical model leads to the same results (curve 4). However, also for Inexact knowledge of the spectral dependence $\tilde{\tau}_i(0, \xi)$ ($\tilde{\alpha}_i$ from Ref. 9, but the correction of $P_i(0, \xi, \theta_j)$ from the results of the restoration of $\tau_i(0, \xi)$ corresponding to curve 5 in Fig. 2 with $\alpha_i = \tilde{\alpha}_i / 2$), the profile $T_s(\xi)$ is determined with the same degree of success (curve 5 in Fig. 4). The poor sensitivity to the possible errors in the parameterization of the spectral dependence of the nonselective component $P_i^n(0, \xi, \theta_j)$ of the transmission function of the channels in the CO_2 absorption band at 15 μm in the determination of $T_s(\xi)$ can be explained by the smoothing effect of the weight function $W_i(\xi)$ (the kernels of Eq. (3)), the form of which are not that of the quantities $P_i(0, \xi, \theta_j)$ in the correction of the optical model of the atmosphere determines the accuracy of the restoration of $T_s(\xi)$. From this point of view the choice of values of α_i based on Ref. 10 is possible (curve 4 in Fig. 1). However, completely neglecting the possible spectral dependence of the unknown corrections of $\tau_i(0, \xi)$, as was noted in Section 2, can lead to unsatisfactory results.

CONCLUSIONS

In this paper we have devised a possible approach to the solution of the complex problem of the spectral-angular thermal sensing of the Earth from space. Only regularization of the solutions of the corresponding inverse problems can. guarantee the reliable determination of the unknown parameters.

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