EFFICIENCY OF THE THREE-ANGLE METHOD FOR DETERMINING THE TEMPERATURE OF THE OCEAN SURFACE FROM REMOTE MEASUREMENTS OF THE IR RADIATION FROM SPACE

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A model analysis of comparative effectiveness of two- and three-angle schemes for determining the temperature of the ocean surface is performed in the approximation of an absolutely black surface and a clear and aerosol-free atmosphere. The estimates were obtained using the method of local linearization of the transfer equations; this method makes it possible to take into account a priori informationabout the variability of the atmosphere in different regions. It is shown that the use of the three-angle scheme is justified under conditions when the errors in recording the IR radiation are reduced to ~ 0.01 K.

Two-channel methods for determining the temperature of the ocean surface (TOS) from remote IR measurements, both spectral and angular, are widely accepted.[1–7] At the same time, methods based on measurements of the angular structure of the outgoing radiation, as a whole, have been proposed in order to take into account more accurately the distorting effect of the atmosphere.[8,9] However these methods have not yet been adequately checked in practice and they require further comprehensive analysis.

Depending on the source of errors and distortions, different authors use different techniques to investigate theoretically the effectiveness of remote methods for determining the TOS. An approach to the analysis of the two-channel methods (spectral and angular) of atmospheric correction that takes into account the variability of the vertical profiles of the temperature and moisture content of the atmosphere in the bottom layers of the atmosphere as multifactor noise is developed in Refs. 6 and 7. Such an approach was used earlier in Ref. 10. It is based on the general principles for solving inverse problems of remote sounding.[11] In this paper this approach is employed to analyze the three-angle method for determining the TOS. One of the basic problems here is to compare the relative efficiencies of the two- and three-angle methods.

The scheme of the analysis, the radiation model, all initial assumptions, and the basic notation employed here are identical to those described in Ref. 7, so that we shall not discuss them here. Increasing the number of measuring channel (the viewing angles), however, required modification of the working formulas used to obtain estimates of the accuracy of the determination of the TOS and the optimal coefficients α_j in the expression

$$\hat{T} = \alpha_0 + (\vec{\alpha}, \vec{T}_r), \tag{1}$$

where $\vec{T}_r$ is a three-dimensional vector of the radiation temperatures measured at three angles, $\vec{\alpha}$ is a three-dimensional vector with the components a_j (j = 1, 2, and 3), and the parentheses indicate I a scalar product of the enclosed vectors.

Assuming, as done in Ref. 7, that

$$\alpha_0 = T^{(0)} - (\vec{\alpha}, \vec{T}_r^{(0)}), \tag{2}$$

$$(\vec{\alpha}, \vec{\tau}) = 1, \tag{3}$$

where $\vec{\tau} = \frac{\partial \vec{T}_r}{\partial T}$, we obtain the following expression for the error in determining the TOS in the linear approximation:

$$\hat{T} - T = (\vec{\alpha}, \vec{a} + \vec{\varepsilon}), \tag{4}$$

where $\vec{\varepsilon}$ is the vector of errors in the measurements of the radiation; $\vec{a}$ is the vector of variations of the radiation temperature which are associated with the atmospheric parameters:

$$\vec{a} = \sum_{1=1}^{2N} \frac{\partial \vec{T}_p}{\partial x_1} \cdot \Delta x_1,$$

where $\Delta x_1 = x_1 - x_1^{(0)}$ are the variations of the moisture content and temperature of the atmosphere

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at N altitudes. The "zero" superscripts here and in the formula (2) denote the point of linearization, for which the climatic values of the parameters are employed.

Using the conditions (2) and (3) and the expression (4) the following formula can be derived for the variance of the errors in determining the TOS:

$$\sigma^2 = (\vec{\alpha},\ \Phi\vec{\alpha}), \tag{5}$$

where the matrix Φ is the covariation matrix of the sum $\vec{a} + \vec{\varepsilon}$, i.e., factors that interfere with the determination of the TOS.

The matrix Φ is determined by the statistical properties of the variability of the atmosphere and the errors in the measurements of the radiation. If the covariation matrix of the parameters of the atmosphere x_1 is denoted by G and the matrix formed from the vectors $\frac{\partial \vec{T}_r}{\partial x_1}$ as the columns ($i = 1, \ldots, 2N$) is denoted as H, then

$$\Phi = HGH^T + \sigma_n^2 E,$$

where E is the three-dimensional unit matrix, the superscript "T" denotes transposition, and σ_n^2 is the variance of the errors in recording the radiation temperatures. The errors for different viewing angles are assumed to be uncorrelated, they are assumed to have zero mean values, and their variances are assumed to be the same

The physical meaning of the conditions (2) and (3) employed in deriving the formula (4) is discussed in Ref. 7, so that we shall not discuss it here.

The optimal vector $\vec{\alpha}$ is determined by minimizing σ^2 taking the condition (3) into account. The method of Lagrange multipliers leads to the following expressions for the optimal $\vec{\alpha}$ and determining the temperature of the ocean surface:

$$\vec{\alpha} = \frac{\Phi^{-1}}{(\vec{\tau},\ \Phi^{-1}\vec{\tau})}; \qquad \sigma^2 = (\vec{\tau},\ \Phi^{-1}\vec{\tau})^{-1}.$$

Like in Ref. 7, concrete calculations were performed for the spectral interval 900–920 cm^{-1} with the help of a radiation model, taking into account the continual and selective components of absorption of radiation by water vapor. This model was found to give results that are analogous to those obtained with the well-known program LOWTRAN-5, but it is more convenient for performing such calculations. The ocean surface is assumed to be absolutely black. The matrices G and the reference altitude profiles of the temperature and moisture content of the atmosphere x are given according to Ref. 12 for different regions and seasons. The computational scheme is described in greater detail in Ref. 7.

It is also assumed that one of the viewing rays is directed vertically at the nadir while the other two rays are oriented at angles θ_2 and θ_3 to the vertical (at the point where the rays intersect the ocean surface taking into account the sphericity of the earth). In this paper the angle θ_3 is set equal to 60° and the dependence of the errors in the determination of the TOS on the choice of θ_2 is analyzed; in addition, $\theta_2 < \theta_3$. When the two- and three-angle methods of measurement are compared we shall denote the corresponding values of σ as σ_2 and σ_3. For the two-angle method the second angle is also denoted as θ_2 and the first angle is equal to zero.

It is desirable to check the three-angle method first under atmospheric conditions which result in the highest errors in the determination of the TOS by the two-angle method. According to Ref. 7, from this viewpoint, the region 4.3 during the fall (according to the classification of Ref. 12), which was chosen for detailed analysis, is the most unfavorable region. This region includes a large part of the Indian Ocean northward of the equator (Ref. 12 contains data only from the northern hemisphere).

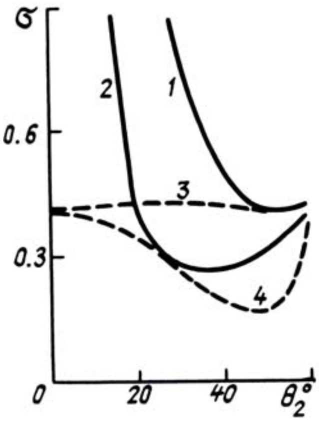

FIG. 1. The errors in determining the TOS by the two-angle method (1 and 2) and the three-angle method (3 and 4) for two degrees of errors in the measurements σ_n: 0.05 *(1 and 3) and* 0.01 K *(2 and 4) (the atmosphere is of the type "fall* 4.3"*).*

Figure 1 shows for this atmospheric situation the dependence of σ_2 and σ_3 on θ_2 for two levels of errors in recording the radiation temperature. For $\sigma_n = 0.05$ K the quantity σ_3 is virtually independent of θ_2 and the optimal value $\alpha_2 \approx 0.39$ K is reached for $\theta_2 \approx 50°$. In the interval 50–60° remains virtually constant, but it increases substantially as θ_2 decreases. It is pointless to study $\sigma_n > 0.05$ K, since the fact that σ_3 is constant as a function of θ_2 actually means that the three-angle method degenerates into the two-angle method. This effect will be studied in greater detail below.

As σ_n decreases to 0.01 K the picture changes appreciably — an extremum also appear for σ_3 (at

$\theta_2 \approx 50°$), and the position of the extremum of σ_2 shifts to $\theta_2 \approx 35–40°$.

In order to understand better the physical mechanisms for these dependences the variance of the errors in determining the TOS can be represented as follows:

$$\sigma^2 = \sigma_n^2 \sum_{j=1}^{3} \alpha_j^2 + \sigma_a^2 ,$$

where σ_a^2 denotes the contribution of atmospheric noise. Examples of the numerical values of the quantities appearing in this formula are given in Table I for the atmosphere "fall 4.3" for different values of σ_n. Here the angle $\theta_2 = 50°$ for the three-angle method and $\theta_2 = 40°$ for the two-angle method in accordance with the optimal values of this angle for $\sigma_n = 0.01$ K.

TABLE I.

σ_n, K	Three angle, $\theta_2 = 50°$			Two angle, $\theta_2 = 40°$		
	σ, K	σ_a, K	$\sqrt{\sum \alpha_j^2}$	σ, K	σ_a, K	$\sqrt{\sum \alpha_j^2}$
0.	0.03	0.03	18.7	0.25	0.25	8.5
0.01	0.17	0.08	15.2	0.26	0.25	8.5
0.05	0.39	0.31	4.6	0.50	0.25	8.5

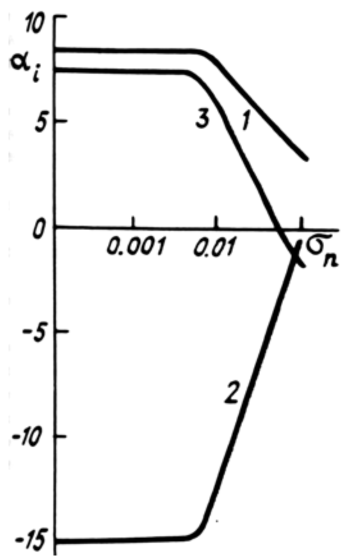

FIG. 2. The coefficients α_j *of the three-angle method for the variant* $\theta_2 = 50°$ *("fall 4.3"* atmosphere).

Figures 3 and 4 show the values of α_j obtained in the three-angle method with $\sigma_n = 0$ for all 48 regions from Ref. 12. The values of σ_3 are close to

One of the basic differences between these two methods is that $\sigma_3 \approx 0$ for $\sigma_n = 0$, while σ_2 is substantially different from zero. But this is achieved at the expense of a significant increase in $\Sigma\alpha$ for the three-angle method, a consequence of which Is that σ_3 depends strongly on σ_n. This in turn leads to the fact that the optimal coefficients α_j of the three-angle method also depend on σ_n, while for the two-angle method in the range of values of σ_n studied the coefficients α_j remain constant as σ_n increases.

The dependence of α_j on σ_n for the three-angle method is shown in Fig. 2 ("fall 4.3" atmosphere; $\theta_2 = 50°$). The value of α_j starts to increase appreciably at $\sigma_n \approx 0.005$ K as σ_n increases.

One of the basic properties of the coefficients α_j in the three-channel methods of atmospheric correction is that $\alpha_1 > 0$, $\alpha_2 < 0$, and $\alpha_3 > 0$. It is assumed that the channels are numbered in the order of decreasing transmission of the atmosphere.[2,5] In our case these conditions are satisfied only for sufficiently small values of σ_n; when σ_n increases up to approximately 0.06 K the three-angle method degenerates into the two-angle method, since in this case $\alpha_2 = 0$. For $0.06 < \sigma_n < 0.1$ K measurements at angles of θ_2 and θ_3 appear in the formula for calculating the TOS with approximately the same (negative) coefficients, since they are virtually identical. There is no point in studying even larger values of σ_n.

Thus the results obtained indicate that the three-angle method has an advantage over the two-angle method only for small errors in the detection of the radiation.

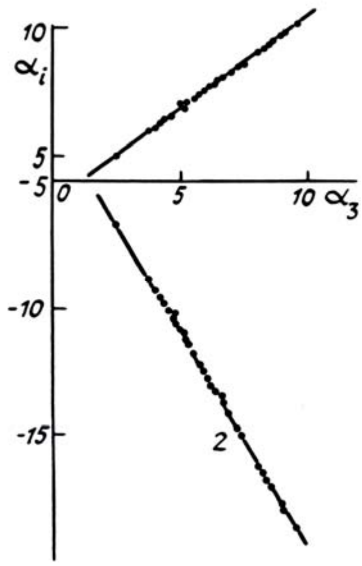

FIG. 3. The relations between the coefficients α_j *for 48 regions from Ref. 12 with* $\sigma_n = 0$ and $\sigma_2 = 50°$.

zero ($\lesssim 0.03$ K), so that there is no need to discuss their properties for different regions. The coefficients α_j satisfy, with high accuracy, the conditions

$$\alpha_1 + \alpha_2 + \alpha_3 = 1;$$
$$\alpha_1 = 0.73\alpha_3 + 3.30;$$
$$\alpha_2 = -1.73\alpha_3 - 2.30$$

and vary from one region to another in a single-parameter fashion. The dependence of α_3 (and hence of α_1 and α_2) on the integrated moisture content of the atmosphere Q reveals a more complicated behavior than for the two-angle method.[7] For the three-channel method the specific nature of this dependence consists of the fact that not only Q but also the temperature of the atmosphere affect α_j (here T_0 is the air temperature at the surface of the ocean, which is equal to TOS).

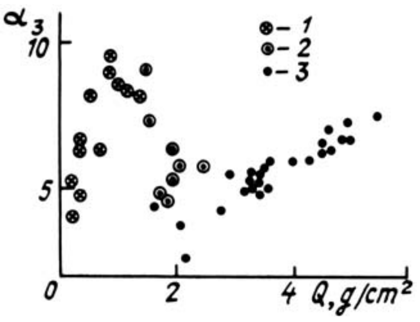

FIG. 4. The values of the coefficient α_3 *for 48 regions from Ref. 12 for* $\sigma_n = 0$ *and* $\theta_2 = 50°$: *1)* $T_0 < 280$ K; *2)* $280 < T_0 < 290$ K; *3)* $T > 290$ K

The computational results presented reflect the basic characteristics and trends observed in the dependences of the coefficients α_j and the accuracy in the determination of TOS by the three-angle method as a function of the angle θ_2, the errors in the recording of the radiation, and the regional atmospheric conditions. In obtaining them only the absorption by water vapor was taken into account in the radiation model of the atmosphere, so that the specific numerical estimates should not be regarded as final. At the same time, it is clear that when the variations of the vertical profiles of the moisture content and air temperature are taken into account the three-angle method has am advantage over the two-angle method only if the values of σ_n are sufficiently small: $\sigma_n \sim 0.01$ K. From this we can conclude that for the actual errors in recording the radiation using modern radiometers ($\sigma_n \approx 0.05$–0.1 K) there is no use in performing measurements at three and more angles. The effective error level σ_n can be reduced to some extent by averaging over a series of adjacent readings, as was proposed, for example. In Ref. 13, but this question requires further critical analysis in practice.

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