EFFECT OF NONBLACKNESS OF THE OCEAN SURFACE ON THE ACCURACY IN DETERMINING ITS TEMPERATURE FROM ANGULAR IR MEASUREMENTS FROM SPACE

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Within the scope of the previously proposed approach to the analysis of the errors in determining the temperature of the ocean surface based on the use of statistical data on the variability of the atmosphere, the role of the ocean surface distinction with respect to an absolutely black emitter is investigated. An account of this factor in a radiation model results in an increase of the errors and an emergence of a minimum in their viewing–angle dependences. The efficiencies of the two– and three–angle measurements are compared.

The main interference in determinatiing the temperature of the ocean surface (TOS) from remote measurements from space of IR–emission is water vapor in the atmosphere. A new approach to theoretical analysis of the techniques for atmospheric correction was implemented in Refs. 1 and 2, which is based on a local linearization of the radiative transfer equation and makes it possible to take into account the regional peculiarities of the variability of the vertical profiles of the moisture content and temperature of air. The two– and three–angle measurements were considered there. In so doing, however, a simplified radiation model with absolutely black underlying surface was used. The real ocean surface differs from the absolutely black one, especially at large observation angles.

The purpose of this paper is a refinement of the previous results obtained with an account of this difference. Moreover, in comparison with Refs. 1 and 2, we have extended the range of the angles being analyzed from 60 to 70°. We analyze a scheme of measurements in the spectral interval 900–920 cm^{-1}. One of the viewing direction is specified as vertical. The second and third directions are assigned by the angles θ_2 and θ_3, which are counted off between the viewing rays and the local vertical at the point where the ray intersects the ocean surface (with the earth's sphericity taken into account). All vector quantities, which are used below, have components along the first two or all three directions.

The method for determining the TOS is given by the linear relation

$$\hat{T} = \alpha_0 + (\boldsymbol{\alpha}, \boldsymbol{T}_r) ,$$

where $\boldsymbol{T}_r$ are the radiative temperatures of one and the same surface element measured from space at two or three angles. The parentheses denote a scalar product, α_0 and $\boldsymbol{\alpha}$ are the parameters which are constant for a given region, for which a local linearization has been carried out. The components of the vector $\boldsymbol{\alpha}$ will be denoted below as α_j.

When the values of α_0 and $\boldsymbol{\alpha}$ are optimal the variance of the errors in determining the TOS is estimated based on the formula[2]

$$\sigma^2 = (\tau, \Phi^{-1}\tau)^{-1} ,$$

where $\tau = \dfrac{\partial \boldsymbol{T}_r}{\partial \boldsymbol{T}}$ is the vector of the derivatives of the radiation temperatures with respect to the TOS. The matrix Φ has the form

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

where σ_n^2 is the variance of the errors in the recording of $\boldsymbol{T}_r$, H is the matrix composed of the column vectors of the radiative temperature derivatives with respect to the atmospheric parameters at different levels, H^{T} denotes the transposition operation, G is the covariation matrix of these parameters and is given according to Ref. 3 individually for each region, and E is the unit matrix.[2] In what follows, σ_2 and σ_3 imply the quantities σ for the two– and three–angle methods with optimal values of σ_0 and σ, at the given observation angles.

The elements of the vector τ and the matrix H were calculated as finite differences based on the resulting variations of the TOS and the vertical profiles of the atmospheric parameters.[1] In so doing, T_r were determined by inverting Planck's function $T_r = B^{-1}(I)$ in terms of the radiation intensities I, which for each observation angle θ were calculated according to the formula

$$I(\theta) = \Big[\varepsilon(\theta) \cdot B(T) + (1 - \varepsilon(\theta)) \overset{\downarrow}{I}_{\mathrm{a}}(\theta^*) \Big] \cdot t(\theta) + \overset{\uparrow}{I}_{\mathrm{a}}(\theta) , \qquad (1)$$

here $\overset{\downarrow}{I}_{\mathrm{a}}$ and $\overset{\uparrow}{I}_{\mathrm{a}}$ are the intensities of downward and upward emission of the atmosphere, whose calculations simultaneously with calculations of the transmission t, were performed with the help of a program LOWTRAN–5; ε is the degree of the surface blackness, $\theta^* = 180° - \theta$ is the angle supplementary to θ, and T is the temperature of the ocean surface.

Relation (1) is valid for an absolutely smooth surface. In this case the degree of the blackness of the ocean–water is calculated from the formula $\varepsilon_f = 1 - r_f$, where r_f is Fresnel's reflectance depending on the complex refractive index n and the angle θ. The values ε_f, used in this paper, have been obtained based on Fresnel's formulas with $n = 1.162–0.0938$ (Ref. 4), and are given for the fixed θ in Table I. The main

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peculiarity of the dependence $\varepsilon_f(\theta)$ is its closeness to unity at the angles $\theta < 40°$ and subsequent steep decay with θ.

TABLE I.

θ,°	ε_f
0	0.99252
40	0.99027
50	0.98477
60	0.96725
70	0.90960

In the presence of waves on the ocean surface, the effective emissivity ε^*, which has been calculated, e.g., by Masuda et al. in Ref. 4, should be substituted for ε_f in front of $B(T)$ in formula (1) and a complex integral relation, in which the angular structure of the downward emission of the atmosphere and the statistics of the slopes of the reflecting surface elements enter, should be substituted for the second term in brackets. On the whole, the calculation of both ε^* and the radiation reflected from a rough ocean surface is a quite cumbersome problem. Its solution is beyond the scope of this paper and the calculations made here refer to the case of a flat reflecting surface. Note that, as follows from data given in Ref. 4, the difference of ε^* from ε_f is much less than the difference of ε_f from unity, and it suggests that the main effects associated with the nonblackness of the real ocean surface will be reproduced within the scope of this simple model.

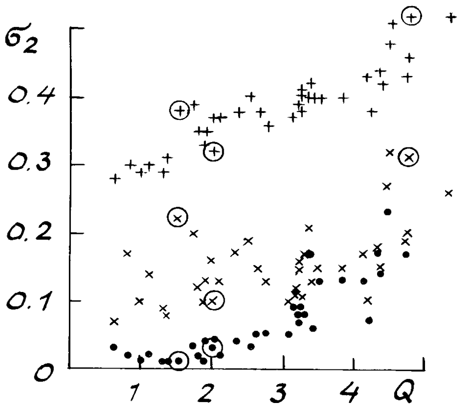

FIG. 1. Values of σ_2 *(*$\theta_2 = 55°$*) in the regions specified in Ref. 3 for* $\varepsilon = 1$ *and* $\sigma_n = 0$ *(dots);* $\varepsilon = \varepsilon_f$ *and* $\sigma_n = 0$ *(crosses); and,* $\varepsilon = \varepsilon_f$ *and* $\sigma_n = 0.1$ K *(pluses). The model of the atmosphere, shown in Fig. 2, are identified by circles.*

We have performed calculations aimed at elucidation of the accuracy of determining the TOS vs the state of the atmosphere, the observation angles, and the employed model of the ocean surface ($\varepsilon = 1$ is the absolutely black surface and $\varepsilon = \varepsilon_f$ is the reflecting flat surface). The main calculated results are shown in Figs. 1–3.

In Fig. 1 the accuracy of the two–angle method is plotted as a function of the integrated moisture content of the atmosphere Q (the choice of the angle $\theta_2 = 55°$ is motivated below) for those regions specified in Ref. 3, in which the temperature of the lower layer of the atmosphere is above $-5°$C. For a number of the models of the atmosphere an account of nonblackness of the ocean surface leads to the overestimation of the errors in determining the TOS σ_2 and, in contrast to the variant with $\varepsilon = 1$, for some models of the atmosphere with Q close in values these estimates substantially differ. This effect is stronger manifested in mid latitudes. The largest values of σ_2 for the mid–latitude model of the atmosphere approach the values typical of the tropical regions. When the level of the errors in recording the emission $\sigma_n = 0.1$ K the accuracy of determining the TOS for all models of the atmosphere lies within the limits 0.3–0.5 K. In the tropical regions with large Q the deficit of the ocean surface emission owing to the difference of ε from unity is significantly compensated by the contribution of the reflected radiation and more intensive downward emission of the atmosphere thereby weakening the effects of the nonblackness of the ocean surface.

As regards the coefficients α of the two–angle method, an account of the difference of the ocean surface from the absolutely black has virtually no effect on them, so that we will not discuss this question here.

For the analysis of the angular dependences $\sigma_2(\theta_2)$, three typical atmospheric situations are shown in Fig. 2. They were indicated by circles in Fig. 1. The calculated results for $\varepsilon = 1$ and $\varepsilon = \varepsilon_f$ are compared.

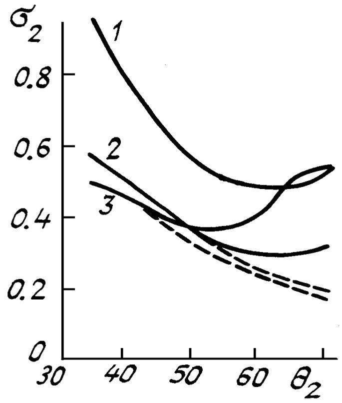

FIG. 2. Angular dependences of σ_2 *for* $\sigma_n = 0.1$ K *for the three atmospheric situations: "fall 4–3" (1), "summer 3–5" (2), and "winter 3–4" (3). The solid curves indicate* $\varepsilon = \varepsilon_f$ *and the dashed curves –* $\varepsilon = 1$.

The "fall 4–3" atmosphere corresponds to the tropical regions in the Indian Ocean and refers to the case in which the values of σ_2 are maximum and the integrated moisture content $Q = 4.8$ g/cm^2 is almost the largest. Here the estimates of the errors in determining TOS by the two–angle method are insensitive to the surface model being employed to within 0.01 K. The "winter 3–4" region incorporates the water areas of the Gulf Stream and the Gulf of Mexico. The "summer 3–5" region is the Eastern subtropical region of the Pacific Ocean. These models of the atmosphere have the moisture contents close in values (Q = 1.5 and 2.0 g/cm^2, respectively), but despite this fact for $\varepsilon = \varepsilon_f$ the first model of the atmosphere possesses the largest value of σ_2 among the situations with Q 4 g/cm^2 while the second model of the atmosphere has the smallest. These atmospheric situations are the examples of the extreme cases of the maximum and minimum difference in σ_2 for $\varepsilon = 1$ and $\varepsilon = \varepsilon_f$. As can be seen from Fig. 1, there are situations with Q close in values and still greater difference in σ_2, but they refer to the continental regions.

When choosing the second angle in the range $Q_2 < 45$–$50°$ for all models of the atmosphere an account of the nonblackness of the ocean surface has virtually no affect on the accuracy of the two–angle method. This agrees with data of Table I, which show that for such angles ε_f differs but slightly from unity. The difference of the ocean surface from the absolutely black one becomes substantial when the angle θ_2 is larger than 45–50°. In this case the angular dependences of the accuracy of determining the TOS for all atmospheric situations for the most part occupy intermediate positions between the three typical examples, shown in Fig. 1.

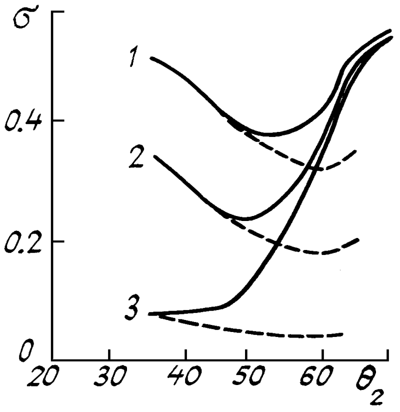

FIG. 3. Angular dependences of σ_2 (solid curves) and σ_3 (dashed curves) for the "winter 3–4" atmosphere with the three values of σ_n in K: 1) 0.1 *, 2)* 0.05*, and 3)* 0.01.

Their important peculiarity for $\sigma_n > 0$ is the existence of the distinctly pronounced minimum, whose position is different for different models of the atmosphere and is associated with the level of the errors in recording the emission (see Fig. 3). For the situations with $Q < 4$ g/cm^2 its emergence depends strongly on an account of the difference of the ocean surface from the absolutely black surface. In the tropical regions the estimates of the errors in determining the TOS with substitution of ε_f for $\varepsilon = 1$ vary insignificantly, but the minimum in the curves $\sigma_2(\theta_2)$ is reached here either. Previously, this was not elucidated in Ref. 1, because the minimum is attained at θ_2 60° (angles larger than 60° were not considered in Ref. 1).

In order to understand the reason of its emergence, let us represent, following Ref. 2, σ_2 in the form of a sum of two terms which describe the interference effect of the atmosphere and the measurement errors

$$\sigma_2^2 = (\alpha, \Phi\, \alpha) = (\alpha, HGH^{\mathrm{T}}\, \alpha) + \sigma_n^2(\alpha, \alpha)\ . \qquad (2)$$

For each region, the first term in this formula increases with θ_2, while the second decreases by virtue of a reduction of the moduli in the components of the vector $\boldsymbol{\alpha}$. The position of the minimum in the curves $\sigma_2(\theta_2)$ is determined by attaining a compromise between these two trends. The increase of the first term in the right side of Eq. (2) with increase of θ_2 is caused by the sensitivity of σ_2 to the interfering effect of the atmosphere, while the moduli of the components of the optimal vector $\boldsymbol{\alpha}$ decrease owing to better conditionality of the inverse problem of determining the TOS based on the measurements of T_r. Directly from formula (2) it is clear that, generally speaking, the angle θ_2, at which the minimum of σ_2 is attained, must depend on σ_n (see Fig. 3).

When the level of σ_n is fixed both terms in formula (2) vary significantly from one region to the other. The different interference effect of the atmosphere is illustrated by the data of Fig. 1, referring to the case in which $\sigma_n = 0$, while the variability of the coefficients $\boldsymbol{\alpha}$ is shown in Ref. 1. Therefore, the position of the minimum θ_2^{opt} varies from one region to the other.

The last circumstance makes a comparative analysis of different atmospheric situations more difficult. The value of σ_2 depends substantially on the angle θ_2 for the "winter 3–4" region. For other models of the atmosphere this minimum is not so pronounced. Analysis of the calculated results shows that, for $\sigma_{\mathrm{n}} = 0.05$–$0.10$ K, an angle of 55° may be taken as a standard compromise value of the angle θ_2^{opt}, applicable to all regions.

The angle $\theta_2 = 55°$ has been already proposed by various investigators for practical use,[5,6] but without discussing its advantages. The existence of a distinctly pronounced minimum of the errors in determining the TOS for the angles convenient for practical use, gives a ground for optical choice of the design of measuring devices.

As noted in Ref. 1, the feasibility of employing the two–angle method of determining the TOS is based on a quite high level of correlation of the interfering effect of the atmosphere at different viewing angles. This correlation is determined by the coefficient ρ, while the estimate of the errors of the two–angle method for atmospheric correction is proportional to $1 - \rho^2$. When calculating based on the model of the absolutely black ocean surface, for most models of the atmosphere with small values of Q, the coefficient ρ is equal to unity with accuracy of three significant digits beyond the decimal point. For this reason, for such models of the atmosphere, the values of σ_2 are close to zero for $\sigma_2 = 0$ (see Fig. 1). Two of the above–considered "winter 3–4" and "summer 3–5" atmospheres belong to these models of the atmosphere. When substituting ε_f for $\varepsilon = 1$ in the model, such a simple structure of the interference effect of the atmosphere is violated and the correlation coefficient ρ decreases thereby resulting in additional errors in determining the TOS. Note that even a slight difference of ρ from unity may result in an appreciable increase of σ_2. When $\theta_2 = 55°$ for the "winter 3–4" atmosphere $\rho = 0.987$, which is the smallest value of ρ. For the "summer 3–5" atmosphere with $\varepsilon = \varepsilon_f$ we have $\rho = 0.998$. For the "fall 4–3" atmosphere $\rho = 0.996$ for both $\varepsilon = 1$ and $\varepsilon = \varepsilon_f$.

Aside from the difference in the correlation coefficient ρ, when $\rho \neq 1$ the amplitude of variations of the atmospheric parameters (characterized by the diagonal elements of the matrix G) also affects the value σ_2. For the "winter 3–4" atmosphere the variations of the moisture content in air in the lower layers, in accordance with Ref. 3, exceed those of "summer 3–5" by a factor of 2–3. Finally when calculating based on the model with $\varepsilon = \varepsilon_f$ this circumstance, together with the difference in the values of ρ, is manifested itself as a substantial difference of σ_2 for these two models of the atmosphere, despite the fact that their integrated moisture contents Q are close in values.

Let us now focus on analyzing the three–angle measurement scheme. In the tropical regions a change–over from $\varepsilon = 1$ to ε_f, just as in the case of measurements at two angles, has no significant effect on the value of σ_3. Here the conclusion drawn in Ref. 2 that the employment of the three–angle method does not yield any advantages over the two–angle method $\sigma_n > 0.05$ K, remains valid. Increasing θ_2 from 60 to 70° has virtually no effect on that conclusion. This fact is illustrated by the data of Table II, which have been obtained for $\varepsilon = \varepsilon_f$ and for optimal angle combinations.

TABLE II.

Atmosphere	σ_n, K	θ_2	θ_3	α_1	α_2	α_3	σ, K
"Fall 4–3"	0.05	55	–	3.42	–2.30	–	0.37
The same	0.05	55	70	4.07	–3.78	0.74	0.35
"Winter 3–4"	0.1	55	–	2.38	–1.36	–	0.38
The same	0.1	60	70	2.31	–1.69	0.43	0.32

Since an account of nonblackess of the ocean surface leads to a significant increase of σ_2 for selected models of the atmosphere with small values of the integrated moisture content, it becomes reasonable to consider additionally the efficiency of the three–angle method under such atmospheric conditions. Figure 3 and Table II give calculated results for the "winter 3–4" atmosphere, with the largest value of σ_2 among the models of the atmosphere with $Q < 4$ g/cm^2. They show that, the three–angle method has an advantage, though a small one, over the two-angle method for this model of the atmosphere with $\sigma_n = 0.1$ K. However, insofar as the gain in σ_3 as compared to σ_2 is nevertheless small for this atmospheric situation, we will not analyze this problem, which is rather of methodical than of principal interest, in detail here.

The performed analysis demonstrates the effects of replacing a unitary degree of blackness in a radiation model by more realistic values corresponding to the smooth ocean surface. In the tropical regions the estimates, previously obtained in Refs. 1 and 2, remain valid. For the selected models of the atmosphere with small moisture content, the errors in determining the TOS increase, and their dependence on the variations of parameters of the atmosphere gets stronger. For real level of the errors in recording the emittance $\sigma_n = 0.1$ K, the accuracy of the two–angle method is within the limits 0.3–0.5 K and the employment of additional measurements at the third angle makes it impossible to increase it significantly. The dependences of the accuracy of determining the TOS by the two–angle method on the choice of the second viewing angle have a distinct minimum near 55°.

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