ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2011, Vol. 47, No. 9, pp. 1092–1096. © Pleiades Publishing, Ltd., 2011.
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Possibilities for Determining Temperature and Emissivity of the Land Surface from Data of Satellite IR Sounders with High Spectral Resolution (IRFS-2)

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Received May 10, 2009

Abstract—Numerical experiments on the simultaneous retrieval of the temperature and spectral emissivity of different land types are performed on the basis of inversion of the simulated high spectral resolution measurements by the IRFS-2 satellite IR sounder. The IRFS-2 data inversion method is based on using a priori information on the spectral behavior of emissivity of different land types and the multiple linear regression technique. The rms errors of determination of the underlying surface temperature using different solving operators are 0.26–0.71 K. The application of the developed IRFS-2 measurement inversion method makes it possible to estimate the land surface emissivity with an rms error not larger than 0.015.

Keywords: surface temperature, spectral emissivity, satellite IR sounder, land surface.

DOI: 10.1134/S0001433811090131

INTRODUCTION

The Earth's surface has been monitored from satellites for several decades. The results of T_s (underlying surface temperature) remote determinations from satellite data have been used in problems of weather numerical analysis and forecasting, hydrology, and agrometeorology and in studies of climate and global changes. Satellite measurements of outgoing IR radiation in the 3.7 and 10.5–12.5 μm air transparency windows are as a rule used to determine T_s. Rather effective remote sensing (RS) technologies are used at present to determine the ocean surface temperature (OST). These technologies make it possible to determine T_s (the temperature of a thin skin layer) with the error of ±(0.6–0.8) K from measurements on polar orbiting satellites under the conditions of clear-sky atmosphere (see, for example, the review (Solov'ev and Uspensky, 1998)).

The present-day OST remote determination methods are based on satellite measurements in two or several channels—transparency windows—with different absorption (Solov'ev and Uspensky, 1998). These methods, which were initially proposed for the two-channel measuring scheme, were called split-window methods (SWMs). Their advantage consists in the possibility of correctly taking into consideration atmospheric absorption of radiation and reaching a high accuracy of determining T_s without using a priori information on vertical temperature $T(p)$ and humidity $q(p)$ profiles at sounding points (p is pressure).

The remote methods for determining T_s (land surface temperature, LST) from satellite data have been developed to a much lesser extent (Uspensky and Shcherbina, 1996; Uspensky et al., 1999; Becker and Li, 1990; Ottle and Vidal-Madjar, 1992; Sobrino et al., 1994; Wan and Dozier, 1996; Mao et al., 2005) and have not been brought to the level of online technologies, which is explained by a much more complexity of the problem, in particular, by the necessity of taking surface non-blackness into account: the surface emissivity $\varepsilon(\nu)$ can be lower than 1 (Salisbury, 1992; Snyder et al., 1998).

The factors that should be taken into account when LST remote determination methods are developed (Uspensky et al., 1999; Becker and Li, 1990; Wan and Dozier, 1996) are as follows:

(i) Land surface non-blackness; i.e., emissivity can pronouncedly differ from 1 (0.8–0.98), varies in the spectrum and space, and is insufficiently known for the series of the main surface types.

(ii) LST varies considerably in space (specifically, within one pixel of a sounding device) and time, as a result of which it is difficult to validate satellite T_s values (by comparing point in situ T_s estimates with spatially averaged values).

(iii) Even if atmospheric absorption of radiation is correctly taken into account T_s and $\varepsilon(\nu)$ cannot be determined with the required accuracy characteristics without using additional information on emissivity because the initial inverse problem is ill-posed.

(iv) The difference $T_s - T_a$ over land, where T_a is the surface air temperature (at a level of ~2 m), can be considerable, which makes it difficult to use standard meteorological observations of T_a (in the network of weather stations) in order to validate T_s values.

The available remote methods for determining LST (from measurements in air transparency windows) somehow take the above factors into account and are reduced to solving the following two subproblems:

(1) estimating and eliminating atmospheric absorption from satellite measurements;

(2) correcting the effects of surface non-blackness and estimating T_s, possibly, with a simultaneous determination of $\varepsilon(\nu)$.

Uspensky et al. (1999) proposed and tested, using the simulated information, the multichannel method of LST remote determination from IASI IR sounder measurements taken in a specially selected set of channels—transparency microwindows (spectral ranges of 1070–1160 and 2130–2133 cm^{-1}). This method cannot be directly applied to IRFS data because data in the HF range (>2000 cm^{-1}) are absent; moreover, additional information on the $\varepsilon(\nu)$ behavior in spectral ranges of the employed subset of channels should be used in order to successfully apply this method.

This work is aimed at considering the possibilities for LST and OST remote determination from atmospheric IR sounder measurements with a high spectral resolution (IRFS-2) within the scope of the developed complex approach to interpreting the above satellite data (Polyakov et al., 2010). This approach can be used to construct sufficiently accurate regression estimates of $T(p)$ and $q(p)$ profiles that should be used to correctly consider atmospheric absorption of radiation, i.e., to solve subproblem 1. We propose to use the method of principal components from (Timofeev and Martynov, 1996), which makes it possible to decrease the dimension of the initial inverse problem, in order to solve subproblem 2, i.e., to obtain T_s and $\varepsilon(\nu)$ values from IRFS data. The paper briefly describes the proposed IRFS-2 data inversion technique (regression) in order to obtain LST and emissivity values and discusses the results of the application of the technique to the simulated IRFS-2 measurements.

METHOD AND INITIAL DATA

To develop the proposed regression technique for inverting IRFS-2 data, it is necessary to form a learning sample, i.e., an ensemble of atmospheric ($T(p)$, $q(p)$, ...) and land surface (T_s, ε) state parameters. For this purpose, we selected the realizations of the atmospheric state parameters from the TIGR databank as was performed in (Polyakov et al., 2010) and completed these realizations with consistent data on T_s and ε. Temperature T_s was simulated by a normally distributed random quantity with the average value $\overline{T}_s = T_a$ (T_a is the surface temperature) and the standard deviation std = 4 K. We formed the data on $\varepsilon(\nu)$ in terms of the principal components (PCs) using the method presented in (Timofeev and Martynov, 1996).

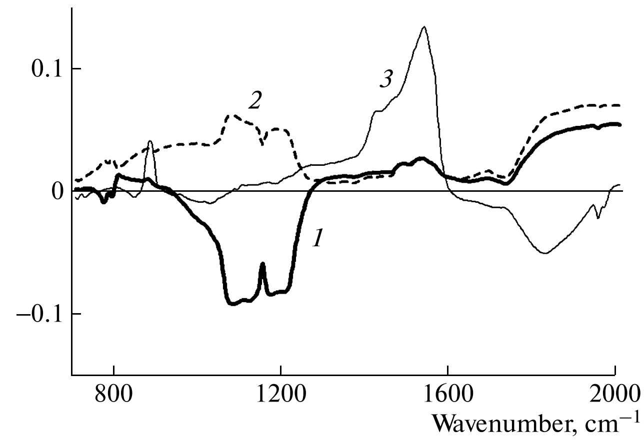

Fig. 1. The first eigenvectors of the emissivity covariance matrix $\varepsilon(\nu)$. The numbers of the vectors are indicated.

The PC set was constructed as follows. The $\{\varepsilon_j(\nu_i), i = 1, 2, ..., n\}$ surface emissivity realizations were selected from the databank including 80 different $\{\varepsilon_j(\nu_i)\}$ dependences experimentally obtained for different Earth surface types in the 5–14 μm spectral region including an air transparency window of 8–12 μm (a spectral resolution of about 2 cm^{-1}), which were kindly provided by Dr. Jack Salisbury (Salisbury and D'Aria, 1992).

When we solved the complex inverse problem in order to determine T_s and ε, we used the method from (Timofeev and Martynov, 1996). For this purpose, we calculated the statistical characteristics of the emissivity realization ensemble based on the above experimental data on $\varepsilon(\nu)$: the average values ($\overline{\varepsilon}$) and the sampling covariance matrix ($\mathbf{C}_{\varepsilon\varepsilon}$). The average emissivity values in the considered ensemble vary from 0.91 to 0.97, and the $\varepsilon(\nu)$ variations change several times over the spectrum (from 0.02–0.03 at the boundaries of the considered 700–900 and 1250–1350 cm^{-1} spectral ranges to 0.05–0.08 in the 1050–1150 cm^{-1} region).

Then, we solved the eigenvector and eigenvalue problem for matrix $\mathbf{C}_{\varepsilon\varepsilon}$. Figure 1 illustrates the first three eigenvectors of covariance matrix $\mathbf{C}_{\varepsilon\varepsilon}$. It is evident that the absolute values of the first eigenvector are maximal in the 1060–1240 cm^{-1} region with the emissivity maximum and its maximum variability. The second eigenvector gives additional information on emissivity in the 900–1060 cm^{-1} region; the third one, on emissivity at about 1550 cm^{-1}.

The set of the highest eigenvectors of the covariance matrix $\mathbf{C}_{\varepsilon\varepsilon}$ (corresponding to the highest eigen-

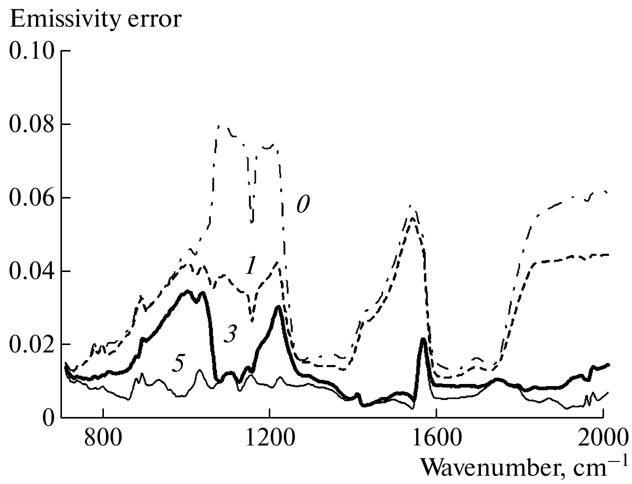

Fig. 2. Error of the emissivity optimal parametric representation $\varepsilon(\nu)$ using the EOB basis of different dimension. The dimension of the basis is indicated; a priori error is marked by *0*.

values) was used as an empirical orthogonal basis (EOB) for the $\varepsilon(\nu)$ optimal parametrization:

$$\varepsilon(\nu_i) = \sum_{\alpha=1}^{\alpha=m} \theta_\alpha \mathbf{f}_\alpha(\nu_i) + \bar{\varepsilon}(\nu_i),$$

where $m \ll n$, and θ are the expansion coefficients or principal components. Figure 2 shows the spectral variations in the emissivity approximation error when EOB with different numbers of eigenvectors is used. A priori variations in the initial ensemble are also shown in Fig. 2 for comparison. Figure 2 indicates that the use of the basis with one eigenvector $f_1(\nu_i)$ results in a considerable decrease in the emissivity a priori variability (from 0.06–0.09 to 0.01–0.02) in the 1070–1180 cm^{-1} spectral region, and the approximation error remains comparable with the a priori variability in the 710–910 and 1260–1350 regions. When three eigenvectors are used, the error is ~0.01–0.03; in the case of five vectors, it is 0.005–0.01 (except narrow regions near 880–900 and 1600 cm^{-1}, where the error increases to 0.015–0.02). Note that we can decrease the error to 0.01 in the entire spectral region (5–14 μm) only when eight eigenvectors are used.

Table 1 presents the rms errors for the $\varepsilon(\nu)$ optimal approximation in the 714–1348 cm^{-1} spectral range in the situation where different numbers of eigenvectors are taken into account in the expansion. Column 0 of Table 1 presents the natural relative rms variations in the emissivity ensemble. Table 1 indicates that it is sufficient to use the first four eigenvectors in order to reach an rms error of no more than 0.01 in the entire spectral region shown above and seven vectors for a error of no more than 0.005. We should note that the approach to the $\varepsilon(\nu)$ parametrization described in (Timofeev and Martynov, 1996) was used to analyze AIRS and IASI data (see, for example, (Li et al., 2007)).

LAND TEMPERATURE AND EMISSIVITY DETERMINATION ERRORS

We experimentally retrieved the land surface temperature and emissivity from IRFS-2 data in order to develop the proposed satellite data inversion method and estimate potential sounding errors. The simulated IRFS-2 measurements (calculated using the atmospheric and surface state parameters from the ensemble described above) as well as the data on the IRFS-2 instrumental errors from (Polyakov et al., 2010)—the relative error varies from 0.2 to 30% depending on the spectral region of measurements (error 1); the error increased by a factor of 1.5–3 (error 2)—were used in the experiments.

Table 2 presents the rms T_s retrieval error using different solving operators (SOs) in the linear regression method. Table 2 indicates that the rms errors of determining the underlying surface temperature vary from 0.48 to 0.71 K for the unified global SO (constructed using all 2311 atmospheric state realizations) and from 0.26 to 0.63 K for localized SOs (i.e., constructed for individual atmospheric and surface state subensembles from (Polyakov et al., 2010)). Note that the use of local SOs can sometimes decrease the rms errors of determining T_s by almost a factor of two.

The errors of determining T_s presented in Table 2 should be interpreted as minimum values. The fact is that the $\bar{T}_s = T_a$ hypothesis was used to construct SO. Indeed, a constant temperature contrast is often observed (see Introduction): $\delta = \overline{(T_s - T_a)} \neq 0$. The experiments performed in (Uspensky et al., 1999)

Table 1. Emissivity optimal parametrization errors (σ) obtained using different numbers of eigenvectors

Number of vectors	0	1	2	3	4	5	6	7
σ, %	0.049	0.025	0.015	0.010	0.0087	0.0072	0.0058	0.0046

Table 2. Root-mean-square error of determining LST obtained using different SOs and a priori uncertainty in the surface temperature (K)

Latitudinal zones	Global SO		Local SO		A priori
	Error 1	Error 2	Error 1	Error 2	
All	0.56	0.64	–	–	18.9
Tropics	0.63	0.71	0.54	0.63	8.6
Midlatitudes 1	0.51	0.59	0.37	0.45	10.0
Midlatitudes 2	0.48	0.54	0.34	0.41	8.15
Polar 1	0.49	0.57	0.26	0.34	9.74
Polar 2	0.53	0.61	0.37	0.46	10.5

indicate that the error of estimating T_s is minimal at $\delta = 0$ and increases with increasing δ.

Figure 3 illustrates the retrieval of the spectral variations in emissivity for two land surface types: (1) soil and (2) coarse sandstone. Good qualitative and quantitative agreement between the emissivity spectral dependences specified in the numerical experiment and obtained as a result of remote sensing is evident. All main maxima and minima in emissivity and singularities in the 900–1300 cm^{-1} region are stably reproduced. Note that the proposed approach to the surface emissivity parametrization makes it possible to rather accurately estimate the emissivity spectral variations in a wider interval (715–2000 cm^{-1}, see Fig. 3), although the atmospheric transparency window is limited to the 780–1200 cm^{-1} spectral range.

The performed numerical experiments made it possible to estimate the $\varepsilon(\nu)$ retrieval rms errors for different land surface types. Note that a priori variation in the tested emissivities is 0.035. Table 3 presents these errors in the situation where the global and local SOs are used in the multiple linear regression method. We recall that the rms approximation error = 0.007 for the employed set of eigenvectors (five) (see Table 1), i.e., accounting for a substantial part of the errors of determining the emissivity obtained in the numerical experiments.

Table 3 indicates that the rms errors of determining the emissivity vary from 0.0129 to 0.0154 depending on the latitudinal belt where the global SO is used and from 0.0106 to 0.0144 for localized SOs, i.e., being smaller by 0.001–0.0023. We can generally conclude that the maximum rms error of the retrieval of spectral variation of emissivity is not more than 0.015.

MAIN RESULTS AND CONCLUSIONS

We performed numerical experiments devoted to a simultaneous retrieval of the temperature and spectral emissivity of different land types on the basis of inversion of the simulated IRFS-2 satellite IR sounder measurements. The IRFS-2 data inversion technique is based on using a priori information about the $\varepsilon(\nu)$ spectral behavior experimentally obtained for different surface types and on the multiple linear regression technique.

The retrieval underlying surface temperature rms errors vary from 0.5 to 0.7 K when the global SO is used. When local SOs (constructed for individual atmospheric and surface state subensembles) are used, the errors decrease to levels of 0.3–0.6 K.

The application of the developed IRFS-2 measurement inversion method makes it possible to estimate

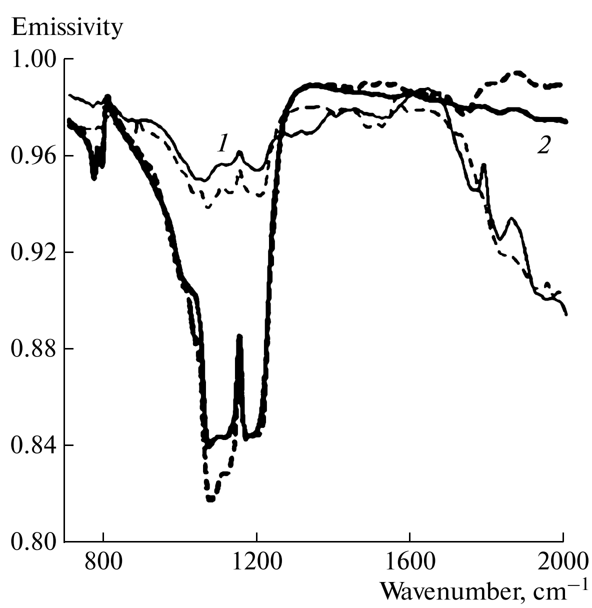

Fig. 3. Examples of retrieving the spectral variations in the underlying surface emissivity: (*1*) soil; (*2*) coarse sandstone. Initial emissivity values in the closed-loop numerical experiment (solid lines) and retrieval results (dashed lines).

Table 3. Root-mean-square error of retrieval of surface emissivity in the 750–1300 cm^{-1} spectral range

Latitudinal zones	Global SO		Local SO	
	Error 1	Error 2	Error 1	Error 2
All	0.0137	0.0147	–	–
Tropics	0.0141	0.0154	0.0132	0.0144
Midlatitudes 1	0.0132	0.0142	0.0119	0.0127
Midlatitudes 2	0.0129	0.0136	0.0114	0.0120
Polar 1	0.0132	0.0145	0.0106	0.0118
Polar 2	0.0140	0.0150	0.0127	0.0134

the land surface emissivity with an rms error no worse than 1.5%.

The obtained error values indicate that the IRFS-2 device potential is high when important land parameters are determined and can be used to specify the solution of the atmospheric temperature–humidity sounding problems using a two-stage procedure (regression + numerical solution of the inverse problem).

ACKNOWLEDGMENTS

This work was partially supported by the Russian Federal Agency for Education (grants nos. 101138 and 393846) and by the Russian Foundation for Basic Research (project no. 09-05-00797-a).

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