Devoted to the 80th anniversary
of Academician V.E. Zuev

The line of inquiry and results of passive satellite sensing of the atmosphere—underlying surface system at the Institute of Atmospheric Optics SB RAS

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A review of results obtained at the Institute of Atmospheric Optics SB RAS on passive sensing of the surface and atmosphere characteristics based on topical processing of satellite images in visible and infrared spectral ranges is presented. The first stage of the investigation was concerned with estimation of disturbing influence of atmosphere on the underlying surface temperature, which resulted in development of a self-radiating model for the atmosphere—ocean system in 3–5 and 8–13 μm transparency windows. Most important factors affecting the radiation attenuation in these ranges have been studied. Using the model, the accuracy of absolute calibration of the thermal channel (10.4–12.6 μm) of the space-borne MSU-SK instrument (Kosmos-1689 and Kosmos-1939) was performed. Further, main regularities in the image formation in visible and infrared spectral ranges when observing through inhomogeneous multicomponent scattering and absorbing atmosphere were studied; the available methods of atmospheric correction of the satellite measurements were mastered and new ones were elaborated. In the last decades, new efficient algorithms of satellite data topical decoding for various applications were worked out, e.g., on-line monitoring, express-detection of forest fires from space, and so on.

Introduction

The Institute of Atmospheric Optics (IAO) was founded in 1969. The concept and main lines of inquiry were determined by Academician V.E. Zuev, who was its director for almost 30 years. During this period, the Institute became widely known for the world scientific community due to impressive successes in elaboration of theory, methods, and instruments for laser sensing of atmosphere, progress in atmospheric spectroscopy and in studies of interactions between optical radiation and determinate and randomly inhomogeneous multicomponent media, as well as of gas and aerosol atmospheric composition.

The Institute was created as a serious complex researching system uniting fundamental and applied scientific branches, naturally complementing each other.

In the beginning of 1970s, highly experienced scientists, as well as graduates of Universities (first of all, Tomsk State University, other Tomsk higher education institutes) were individually invited to the IAO and became its principal creative power. Many their works became widely renowned both in USSR and abroad in a relatively short period of time (the first 10 years). All these works have constituted the nine-volume monograph “Modern Problems of Atmospheric Optics” published under the editorship of Academician V.E. Zuev. The first volume was issued in 1986 (Gidrometeoizdat, Leningrad) and the last one – in 1996 (Publishing House of IAO SB RAS, Tomsk).

This review is aimed at attracting attention of our colleagues to one more research direction initiated by V.E. Zuev, i.e., passive sensing of the Earth surface with satellite means. Any space image of the Earth surface contains some atmospheric traces. They can be either evident (e.g., clouds) or implicit, changing spectroscopic content of the recorded optical radiation or distorting brightness, geometry, and other parameters of objects on the Earth surface or in the atmosphere. These researches can help in study of regularities of optical radiation transfer into scattering and absorbing media, which was among the Institute themes since its foundation.

Remote estimation of the ocean surface temperature

The problem of remote estimation of sea and ocean near-surface temperature with a required accuracy is of great importance, first of all, for weather forecasting. The temperature in points of some uniform grid covering the globe is one of input parameters for weather forecast computer programs. Remote satellite methods of environmental investigation allow the above problem to be practically solvable providing that topical processing algorithms are of sufficient accuracy. The problem of

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distorting effect of atmosphere on the observation accuracy appeared very early in the development of aerospace techniques for passive sensing of the water surface temperature. Thus, the IAO has received two government scientific orders connected with enhancement of efficiency of remote techniques and means for measuring the underlying surface temperature. The task was to elaborate guidelines for improvement of instruments for space sensing of the ocean surface temperature (OST). One more important problem was the ground-truth experiments on control for radiometric sensitivity of the satellite IR instrumentation.

By the time, the Institute had at its disposal all necessary prerequisites to solve the problems successfully: the experience of theoretical and experimental researches, material resources, modern computers, and a highly professional scientific team consisting of about 30 persons (V.V. Fomin, S.V. Afonin, V.I. Khamarin, O.I. Tretyakov, S.M. Sakerin, D.M. Kabanov, B.D. Belan, G.A. Titov, et al.), concentrated mostly at the Laboratory of Sensing Atmosphere with Space Means.

Complexity of the researches required a participation of experts in many fields, such as atmospheric IR spectroscopy, transfer equations both for conditions of light-hazy atmosphere and broken cloudiness. Ground and airborne measurements of light flux parameters and meteorological air conditions were required as well. Therefore, it was necessary to organize and fulfill a number of ground-truth experiments controlling the performance of the satellite MSU-SK instrumentation and to verify the methods accounting for disturbing atmospheric effects on satellite measurements.

We believe that the research program for 1980–1990 was fulfilled perfectly. Its main results included simulation of operation of satellite radiometers of the MSU-SK type through atmosphere under different opto-meteorological conditions of the ocean surface passive sensing; the study of the problem of accounting for and minimization of atmospheric effect in reconstructing OST based on satellite radiometric methods; the development of the radiation transfer model for the ocean–atmosphere system in wave ranges of 3–5 and 8–13 μm; the analysis of available methods of atmospheric correction for OST space sensing; the study of the most important factors affecting the radiation attenuation in atmospheric windows of 3.5–4 and 8–13 μm. Therewith, the 10.4–12.6 μm range was accentuated, because it was the operating range of one of the channels of the MSU-SK satellite instruments designed for environmental purposes, tested, and placed in operation in USSR. The channel had a spatial resolution of 600 m and was used in temperature sensing of the underlying surface.

One more important result was the designed experimental radiometric equipment for ground-truth observations, as well as interpretation of measurement data of the MSU-SK instruments, set at Kosmos-1689 and Kosmos-1939 space satellites, for Canary Islands, Gulf of Bothnia, Black, Caspian, and Azov seas. Important ground-truth experiments on sensing optical properties of atmosphere in sub-satellite points were conducted with participation of the IAO's aircraft laboratory[1] and the scientific-research ship *Akademik Vernadskii* (40th voyage, 1989).

A comparison of radiation temperature measured in two IR channels of the AVHRR device and calculated in view of geometry of satellite observations and optical conditions of atmosphere is presented in Fig. 1. Figure 2 shows a similar comparison for the MSU-SK heat channel.

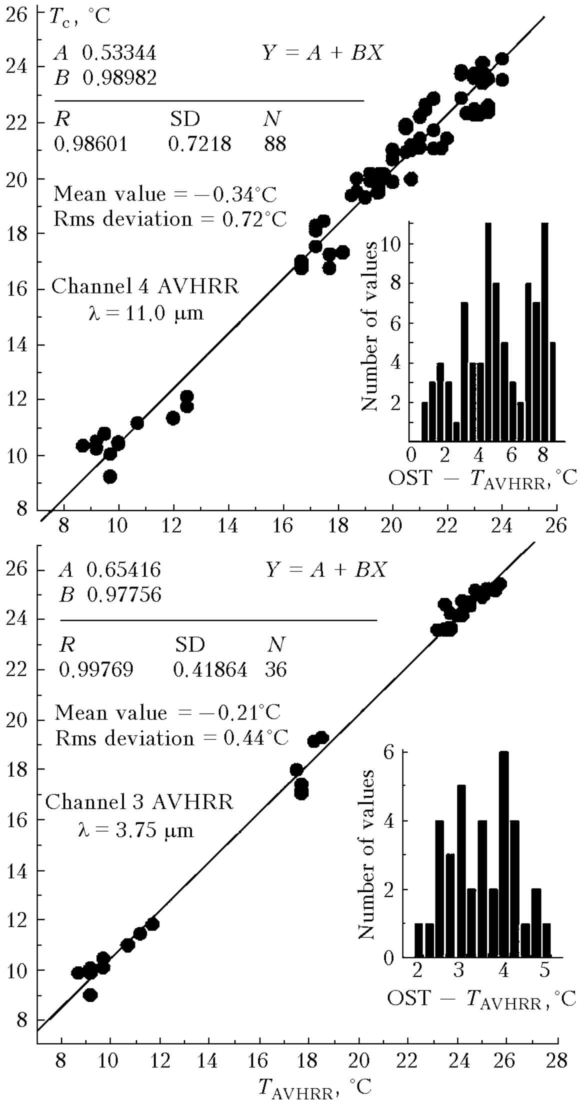

Fig. 1. Comparison of AVHRR-measured (T_{AVHRR}) and calculated (T_c) radiation temperatures.

As is seen in Figs. 1 and 2, the simulated optical signal rather exactly approximates the actual one. These data became a basis for accuracy analysis of interpretation algorithms for space OST measurements and atmospheric correction. Areas of space test observations within the research program carried out from 1982 to 1989 are shown in Fig. 3. Experimental data are presented in Refs. 2–9.

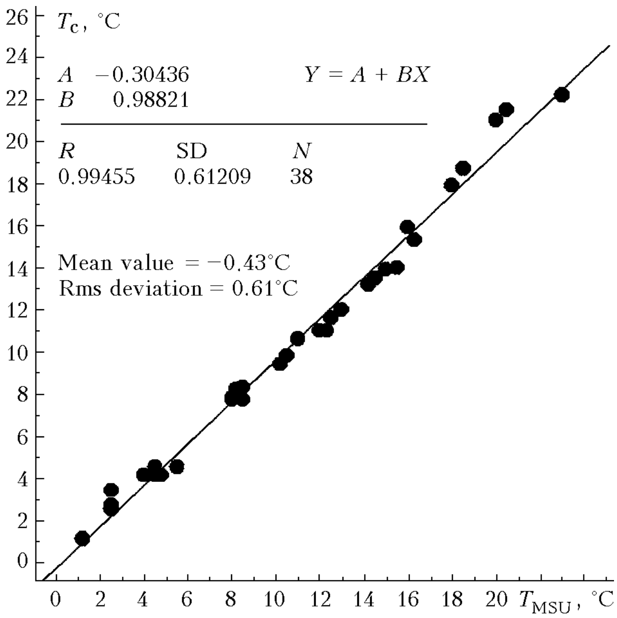

Fig. 2. Comparison of satellite MSU-SK-measured (T_{MSU}) and calculated (T_c) radiation temperatures.

Thus, at the first stage of the above researches, a model was built, which sufficiently accurately accounted for absorption and attenuation of IR radiation in atmosphere, its own radiation in this wave range, as well as the ocean surface emittance. In this case, atmospheric dispersion and solar radiation reflection from surface points adjacent to the point under study were neglected. This was allowable because of the problem specificity, particularly, due to statistical homogeneity of radiation parameters of ocean waters distant from land. At the same time, this restricted the area of applicability of OST reconstruction algorithms by the ocean part, which was 200 km distant from land. As a rule, in this transient region the homogeneity condition of optical water properties is not fulfilled.

Worthy of mention is the experimental procedure at that time. The initial data were ordered beforehand to the date and time of conducting the ground-truth experiments. Then the data on magnetic media were delivered to the IAO, where they were processed. These two stages required manifold organizational time-consuming agreements at different levels. Therefore, for reasons of impossibility to repeat the ground-truth experiments in short time, their reliability was of great importance.

This research program was completed, and, we believe, at a sufficiently high level, thanks to direct organizing participation of Academician V.E. Zuev.

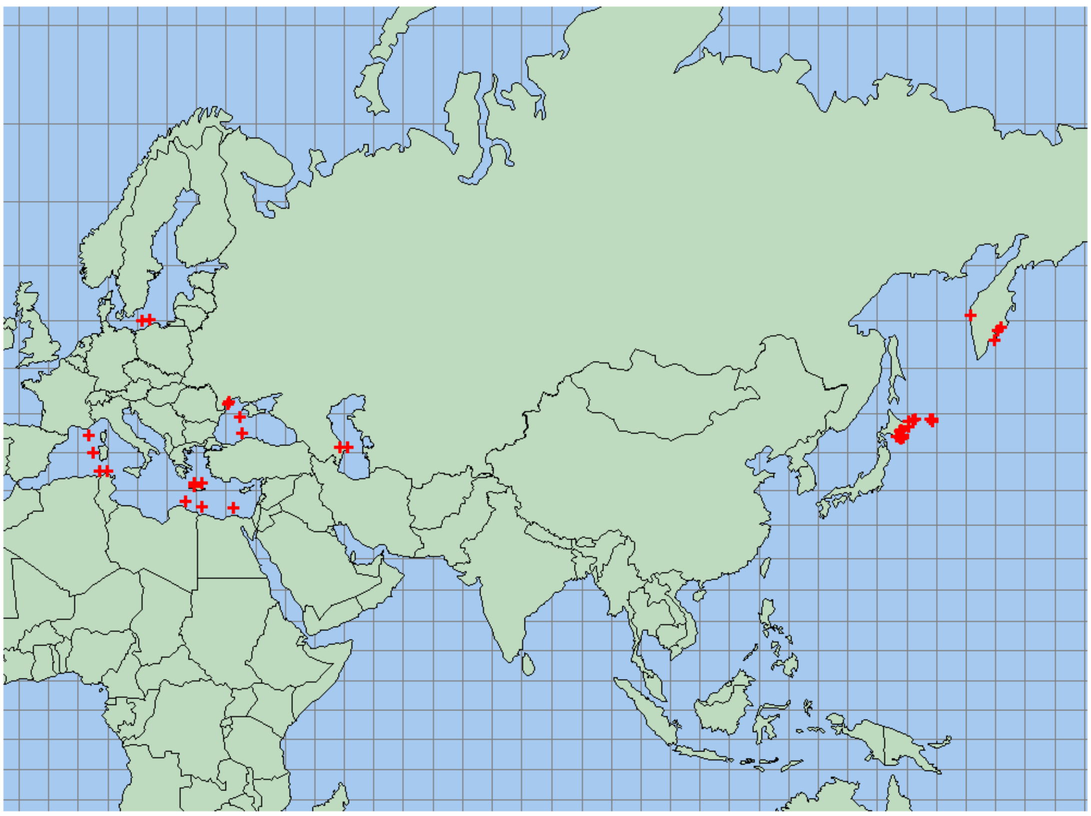

Fig. 3. Sites of satellite MSU-SK test measurements.

Along with the above researches, the processes of the visible-range image formation, scatter and transfer in media of atmospheric types have been studied. The study was carried out both experimentally (V.N. Genin, B.D. Borisov, and V.A. Krutikov) and theoretically (V.V. Belov, I.Yu. Makushkina, and G.M. Krekov). Fully, the results of the study are given in Ref. 10. They can be briefed as follows. Principal regularities of the image side illumination noise, caused by reflection (emission) from object's elements and its background, were established for objects observed through scattering media. The noise effect on vision system parameters, such as isoplanarity, spatial resolution, radius of side illumination, integral side illumination, pulse transfer characteristic, and optical transfer functions of scatter channels, has been studied. Reasons and conditions of image distortion under variations of line-of-sight spatial location of a high-density scattering medium layer were established.

Unfortunately, the disunion of USSR caused a contraction of Russian programs of the Earth space sensing (including the Institute programs) and made inaccessible domestic satellite data.

Nevertheless, we continued the researches of regularities of imaging and image transferring through scattering and absorbing media in the IR range[11–14] with emphasis on particular operating satellite systems (NOAA and AVHRR) due to availability of their on-line images simultaneously in five wave ranges for any earth station without preliminary ordering.

Therefore, when the IAO has received the SkanX station under support of the President of RAS Academician Yu.S. Osipov, the President of SB RAS Academician V.A. Koptyug, and the Head of the Presidium of the Tomsk Scientific Center V.A. Krutikov, the development of cryptographic algorithms for satellite data was continued. And we should again emphasize the decisive role of Academician V.E. Zuev in organization of this work.

Small-scaled thermal anomalies. Technology of atmospheric image correction

By the time of receiving by IAO of the NOAA satellite data-acquisition station, there were already several such stations in service in Siberia (Krasnoyarsk, Irkutsk, Novosibirsk, Yakutsk, and Tomsk) as parts of space environmental monitoring system. As is well known, a wide range of environmental and nature management problems (control for conditions of vegetation cover, water sources, glaciers, state of north seas ice cover, phytoplankton in seas, crop capacities, as well as detection of forest fires, etc.) are theoretically solvable by means of passive satellite sensing methods. Nevertheless, only a few of these problems are solved today at a proper level and the results can be in a regular use. The problem of detecting and monitoring forest fires is among them.

Forest fires are among the powerful natural factors affecting global environmental changes. Consequences of these large-scale catastrophes can be observed throughout the planet. Unfortunately, very often none of the modern fire-fighting techniques but the nature itself can stop this uncontrollable element. Recent fires in the USA, Mexico, Australia, and Russia are characterized by their disastrous effects.

Parameters of the NOAA satellite aggregation and the instrumentation designed for meteorological purposes make them usable in satellite systems of forest fire monitoring, namely: (a) orbit type (polar); (b) orbit height (820–870 km); (c) wide survey limits (almost 3000 km); (d) the number of satellites in the orbit (up to 5 simultaneously), which allows almost every point on the Earth surface to be controlled ten or more times per day; (e) 3.75-μm spectral channel in the AVHRR device (close to the intensity maximum of the forest fire IR radiation); (f) channels in visible and IR spectral ranges (allowing the fires, atmospheric background, and surface objects, indistinguishable in the 3.75-μm channel, to be separated).

However, the wide survey limits determine the main disadvantage of the AVHRR instrument, i.e., its low spatial resolution (1.21 km^2) in a sub-satellite point. This makes it difficult to use the instrument for express-detection of forest fires, which should be considered as the principal problem in the satellite monitoring of forests. This is especially important in cases when the most reliable and tested technique (aerial surveillance) is inaccessible for environmental services (mainly, because of economical reasons).

This problem became of principal interest in the program of creation of means for satellite data topical decoding, realized in IAO since 1997.

Attenuation of IR radiation by atmosphere and the aerosol scattering of solar radiation significantly decrease the efficiency of multichannel AVHRR-images for express-detection of small-size forest fires[15–17] (less than spatial resolution of the device). Based on common regularities of imaging through scattering and absorbing media in visible and IR ranges,[11–14] since 1998 we have directed our efforts to solving the following problems:

– study of influence of geometry of observational conditions on the aerosol and molecular atmospheric scattering contribution into the measured radiation temperature;

– development of informative and methodical foundations for atmospheric correction of AVHRR-images;

– elaboration of new algorithms for topical processing of satellite multichannel images.

An important result of this activity is the creation at the IAO of the system for express forest fire monitoring from space, which is routinely used in the Tomsk Region since 1998.[18–21]

Let us illustrate the obtained results for every above-indicated problem.

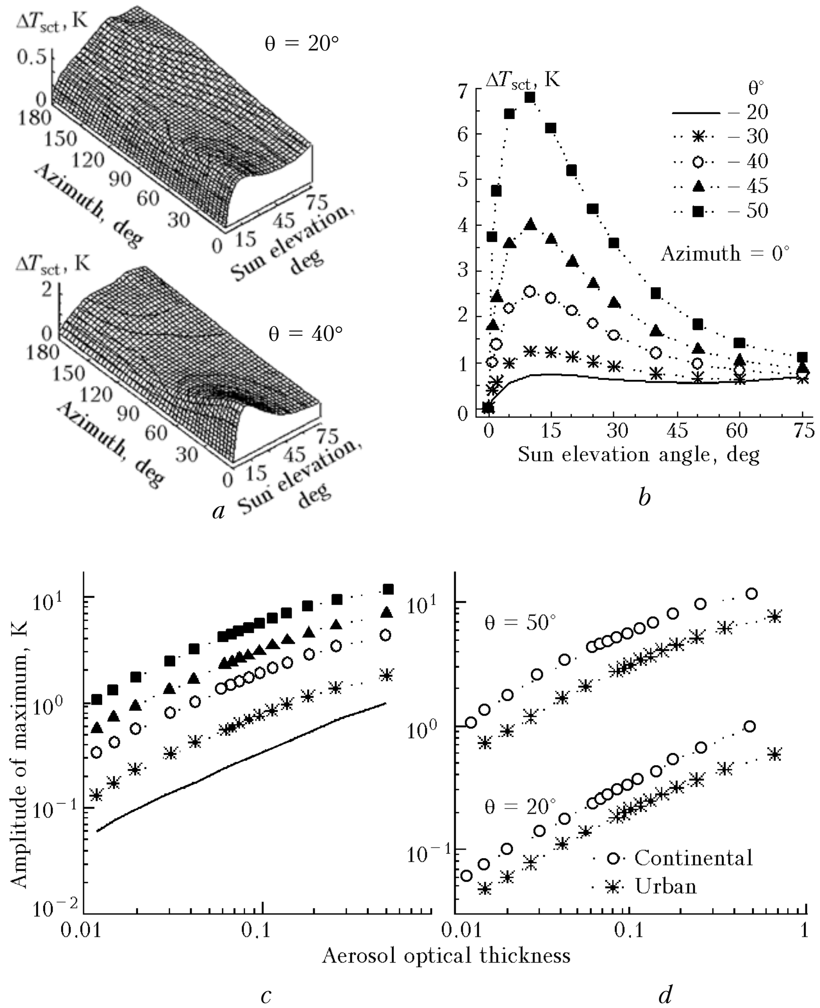

Fig. 4. Contribution of temperature addition ΔT_{sct} into the radiation temperature at the expense of aerosol-scattered solar radiation depending on the geometry of observation (θ is the slope angle of the device axis). The third AVHRR channel (λ = 3.75 μm), continental aerosol (meteorological visibility range is 5 km) (*a* and *b*). Local maximum ΔT_{sct} as a function of θ, AOT of continental and urban aerosol (*c* and *d*).

Figure 4 presents modeling results for geometry dependence of the scattered radiation contribution into signal from some observed point (at a set meteorological visibility range). These conditions include the slope angle θ of the device axis relative to the vertical to the Earth surface, Sun elevation angle Z, and azimuth angle φ between the scanning plane and the plane passing through the vertical and the direction from satellite to Sun.

These results are of interest, because they allow one to clarify occasional temperature anomalies, which occur in AVHRR-images in the thermal channel and are not thermal inhomogeneities on the Earth surface or glares (reflection of solar radiation from cloud boundaries).

This phenomenon is simple by its physical nature: this is the result of solar radiation reflection from the atmospheric aerosol component concerned with the aerosol scattering phase function shape, i.e., at certain angular relations and in the presence of the atmospheric aerosol, radiation, scattered toward the device, can attain its maximum, which exceeds the threshold value in the algorithm of automatic image processing. This results in false alarms.

As can be concluded from Fig. 4, threshold values in threshold algorithms (often used in satellite systems of monitoring forest fires) are not constant and depend at least on θ, φ, Z, and the meteorological visibility range near the Earth surface. In our opinion, this conclusion is valid for other applications using threshold decision algorithms.

Thus, to construct some effective threshold algorithm for satellite data processing, it is necessary to account for effects of optical radiation scattering in atmosphere. Apart from the aerosol component, sources of scattering are air molecules as well (precisely, inhomogeneities in their density). Informative and methodical foundations for atmospheric correction of AVHRR-images distorted by absorption and scattering of the object thermal radiation are presented in Ref. 22.

To conduct the atmospheric correction, it is necessary to eliminate the detected radiation components, which are stipulated by the atmospheric molecular absorption or aerosol attenuation (absorption and scattering). The absorption can be estimated based on the known temperature and humidity profiles; the aerosol influence – based on the known aerosol optical thickness. Some remarks on the aerosol influence should be made. As it was found from the analysis of the scattering effect on the image quality, sometimes the profile of scattering coefficient distribution along the sight line determines the quality rather than the optical thickness of the scattering medium. This is not our case, because of low spatial resolution of the AVHRR device, and the side illumination (which results, in particular, in *t*-effect[10]) can be taken into account integrally via optical thickness of the scattering medium. The light haze magnitude can be quite precisely determined from the atmospheric integral optical thickness.[10]

Using the computer simulation, we have shown[22] how the accuracy in setting meteoparameters (temperature and air humidity profiles) influences the precision of the reconstructed thermal radiation intensity of small-scaled thermal anomalies (SSTA) in the 3.75-μm channel. The ideal conditions for the procedure can be realized provided meteorological and satellite observation data are matched in time, which is practically inaccessible under actual conditions. Figure 5 shows the dependence of atmospheric correction on the accuracy of setting the background temperature of the underlying surface (TUS), as well as the degree of matching in time of meteoparameter measurements and satellite observations. As a rule, the correction is effective provided the time lag between receiving the meteodata and satellite images does not exceed 3–6 h (providing that there is no sharp weather changes).

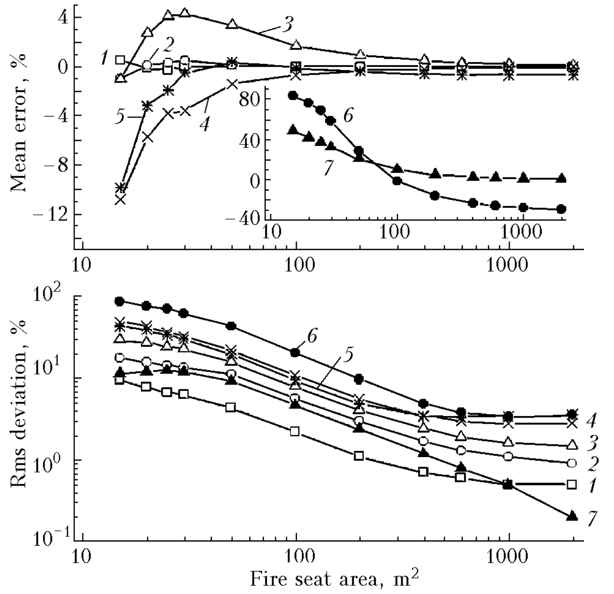

Fig. 5. Influence of *a priori* meteoparameters on the precision of the reconstructed thermal radiation intensity of a fire seat: $\delta t = 0$–1 h (*1*); 0–3 h (*2*); 3–6 h (*3*); 1 day (*4*); 1 month (*5*); without correction (*6*), TUS minus 1 K (*7*).

Figure 6 demonstrates the influence of aerosol on the precision of reconstruction of SSTA thermal radiation intensity.

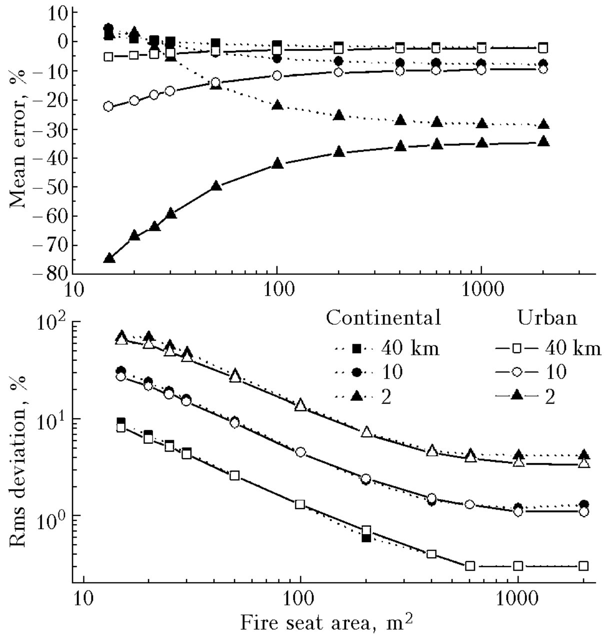

Fig. 6. Influence of aerosol on the precision of the reconstructed thermal radiation intensity of a fire seat; continental or urban aerosol; visibility ranges are of 40, 10, and 2 km.

If the on-line meteodata are inaccessible, the problem can be solved using data from TOVS instruments, which are set in NOAA satellites just for this purpose. Unfortunately, modern software designed for these aims could not be used in personal computers. Therefore, fulfilling the order of the Institute of Cosmophysical Researches and Aeronomy (ICRA) SB RAS, we have adapted it to personal computers.[24]

As is known, there is not any service in Russia at present, which measures optical parameters of atmospheric aerosol; such net is now being formed.[25,26] These parameters are available through AERONET (USA). Therefore, we have made an attempt to reconstruct aerosol parameters with the technique used at the IAO SB RAS and based on IAO measurements and processing of satellite images of the region around the Institute. As a result, the procedure of on-line estimation of aerosol field over the Tomsk region has been realized.[22,23] The result of reconstruction of the field for one event is shown in Fig. 7.

Another way to reconstruct the optical thickness of the atmospheric aerosol component and meteoparameters is the use of data measured by the MODIS instrument installed on TERRA and AQUA satellites (USA, NASA) and the MODIS Atmosphere Products software. We have conducted validation and statistic analysis of MODIS Atmosphere Products data as applied to the territory of the

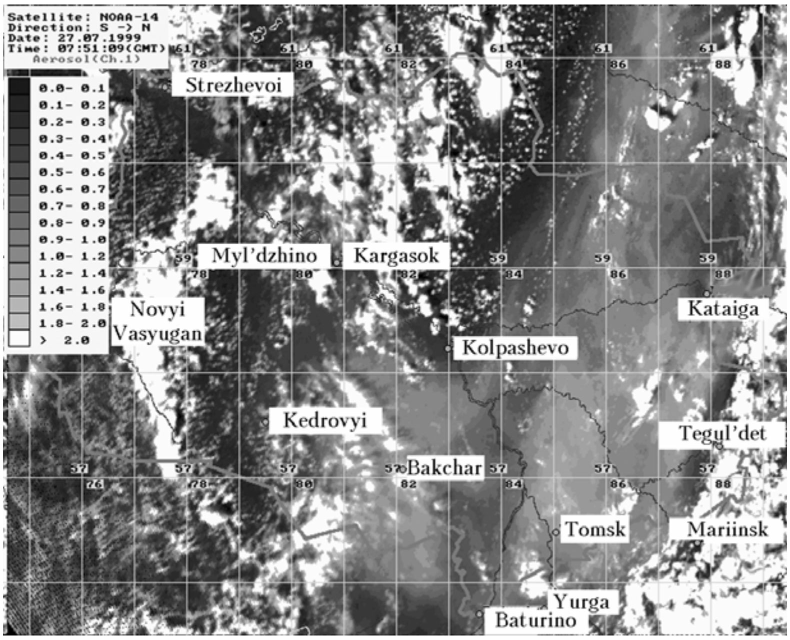

Fig. 7. Spatial distribution of aerosol optical thickness $\tau(x,y)$ (λ = 0.63 μm) in the Tomsk region on July 17, 1999.

Tomsk region,[27–29] where we used time series of ground-based measurements of atmospheric optical parameters (IAO, AERONET). The comparative analysis of satellite and ground-based data on aerosol optical thickness (AOT) has been carried out for 0.47 and 0.66 μm wavelengths. The results of the comparison have shown a good correlation between the data (R = 0.86–0.93), as well as a good agreement between AOT moduli and their time behavior.

The created informative and algorithmic basis for two-component division (atmospheric and ground-based) of an image allows the problem of satellite data topical decoding (in particular, express-detection of small-size forest fires) to be solved in two ways: with the use of the dynamic threshold for decision-making on the base of the above division or via clearing the image from atmospheric background and then solving the problem for a standard (unperturbed) image with approaches and methods used in the theory of the remote sensing, in particular, new algorithms of automated image analysis by K.N. Protasov and his colleagues, based on promising non-parametric approaches.[30–33]

In 2003, fulfilling the order of Rosaviakosmos, the IAO specialists applied the atmospheric correction technique to processing aircraft multichannel images of the Earth surface.

Underline that the proposed technique is not universal and cannot be used for any situation and in any conditions of the passive Earth sensing.

In cases when spatial resolution of measuring instruments is much less than the side illumination radius (see Ref. 10, chapter 6, part 6.3), this procedure can be considered only as zero approximation and should be supplemented with blocks accounting for mutual influence of object's and background's elements on their images, including the blurring effect resulting from the aerosol and molecular scattering.

The efficiency (at least, regional) of the informational-algorithmic technique for express detection of forest fires from space, developed at the IAO SB RAS, is illustrated in Table. Note that we have solved in passing a number of subsidiary, but practically important problems, e.g. more precise satellite data gridding, preliminary automatic check of data quality, estimation of the space monitoring efficiency, etc.

Efficiency of fire detection from space using data of AVHRR and MODIS instruments (Tomsk Region, 2003) (in brackets is the number of prior* detections)

Instrument	June	July	August	September	Sum
AVHRR/IAO	16 (7)	60 (22)	82 (37)	28 (11)	186 (77)
MOD14	7 (4)	28 (11)	53 (16)	10 (6)	98 (37)
MOD14/TERRA	6 (3)	20 (6)	43 (13)	9 (6)	78 (28)
MOD14/AQUA	6 (4)	21 (7)	40 (8)	7 (4)	74 (23)

Note. MOD14 corresponds to MODIS data from TERRA and AQUA satellites, MOD14/TERRA is only from the TERRA satellite, and MOD14/ AQUA is from the AQUA satellite.

* The number of prior detections of forest fires, i.e., detected earlier than they were detected by other services: aviation, forest-guards, etc.

Table contains the number of forest fires detected at the territory of the Tomsk region based on AVHRR and MODIS satellite data processing. Remind that the MODIS instrument outperforms the AVHRR sensor in a number of parameters.

The MODIS data (MOD14 format) were obtained through the standard algorithm of MODIS

Fire Product.[34,35] AVHRR images were analyzed using the technique for express-monitoring of forest fires designed at the IAO SB RAS and used by forest conservation services in the Tomsk region since 1998.

The table data allow the following conclusions. First, the technique for early detection of forest fires from space developed at the IAO SB RAS is twice as effective (at least, regionally) as the globally used standard MODIS Fire Product (MOD14). Second, the optimal technique of fire detection at a global scale must include the regional component; moreover, the latter can outperform the large-scale techniques (departmental, national, international). Last years, this conclusion finds a growing international support.

We connect the further development of this technique with practical realization of the AVHRR block of atmospheric image correction.[22] The results of satellite data processing[36] have demonstrated applicability of the atmospheric correction for SSTA detection even under complex observing conditions.

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We would like to underline once again the role of Academician V.E. Zuev in the choice of promising research problems, which could be solved effectively and at high scientific level just at the Institute of Atmospheric Optics.

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