Mitigation and Adaptation Strategies for Global Change (2006) 11: 113–145 © Springer 2006

SATELLITE MONITORING OF FOREST FIRES IN RUSSIA AT FEDERAL AND REGIONAL LEVELS

E.A. LOUPIAN[1], A.A. MAZUROV[1], E.V. FLITMAN[1], D.V. ERSHOV[2], G.N. KOROVIN[2], V.P. NOVIK[2], N.A. ABUSHENKO[3], D.A. ALTYNTSEV[3], V.V. KOSHELEV[3], S.A. TASHCHILIN[3], A.V. TATARNIKOV[3], I. CSISZAR[4], A.I. SUKHININ[5], E.I. PONOMAREV[6], S.V. AFONIN[7], V.V. BELOV[7], G.G. MATVIENKO[7,*] and T. LOBODA[4]

[1]Space Research Institute (SRI), Russian Academy of Science (RAS); [2]Center on Forest Ecology and Productivity (CFEP) RAS; [3]Institute of Solar-Terrestrial Physics (ISTP) Siberian Branch RAS; [4]University of Maryland: USA; [5]V. N. Sukachev Institute of Forest Siberian Branch RAS; [6]Krasnoyarsk State University; [7]Institute of Atmospheric Optics, Siberian Branch RAS
*(*Author for correspondence: Tel: +7 382 249 2738, Fax: +7 382 249 2086; E-mail: mgg@iao.ru)*

(Received 17 January 2003; accepted in final form 14 June 2004)

Abstract. This paper presents an overview of current satellite-based fire mapping activities at several institutions in Russia that provide operational fire monitoring at federal and regional levels. The current operational systems are based on data from the Advanced Very High Resolution Radiometer (AVHRR) and the TIROS Operational Vertical Sounder (TOVS) on the National Atmospheric and Oceanic Administration (NOAA) operational polar orbiting environmental satellite series. Detailed descriptions of the data acquisition and preprocessing systems, algorithms, and the suite of fire products are provided. Each institution has expertise in addressing a specific aspect of satellite-based fire mapping and monitoring. The methodologies described include proper georegistration of AVHRR data and elimination of false alarms while retaining a high active fire detection rate. Statistical and physical approaches are presented to account for, among other effects, reflection from bright surfaces and clouds, sun-glint, and atmospheric attenuation by smoke and haze. An approach for fire danger estimation is also presented. The fire mapping activities at the various institutions are being organized into a regional network within the international Global Observation of Forest and Landcover Dynamics (GOFC/GOLD) program. Concerted efforts will facilitate the implementation of processing systems for new and improved sensors, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) on the experimental NASA Earth Observing System Terra and Aqua satellites and the Visible/Infrared/Imager/Radiometer Suite on the next generation National Polar Orbiting Environmental Satellite System (NPOESS).

Introduction

At the XI International Boreal Forest Research Association (IBFRA) Conference and Global Observation of Forest Cover/Global Observation of Landcover Dynamics (GOFC/GOLD) Workshop (Krasnoyarsk, Russia, August 5–9 2002), it was repeatedly emphasized that forest fires still remain one of the powerful natural factors affecting global changes in the Earth's environment. Vestiges of these large-scale catastrophic phenomena can be found on every continent. The catastrophic consequences of forest fires in USA, Mexico, Australia and Russia in recent years are well-known. Such events are often caused by insufficient or tardy fire extinguishing measures or by late detection of fires, when the existing technologies cannot enable efficient fire suppression. Often all known fire-fighting technologies prove to be ineffective and fires become catastrophic. Satellite observations, along with the traditional ground- and air-based observing systems, are becoming an increasingly important source of data for early stage fire detection.

The Russian practice of forest fire detection and monitoring using remote sensing is currently based on the processing of Advanced Very High Resolution Radiometer (AVHRR) data on the National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Operational Environmental Satellite series (POES). The network of regional centers of satellite monitoring is growing rather rapidly, thus providing, along with other factors, easier access to satellite information. During the last several years more than 15 such centers have been organized over the territory of the Former Soviet Union. In addition, federal-level systems such as the Arial Forest Protection Service *Avialesoohkrana* (AFPS) were created to monitor either the whole territory of Russia or a portion of the country, such as the Siberian region.

Each center for the reception of satellite information uses its own software for everyday needs. Therefore, depending on the specialization of software developers, in some centers principal attention is paid to the application of GIS technologies, while in others the focus is on detection of burnt forest areas or real-time estimation of fire danger. In some centers the main efforts are concentrated on the improvement of algorithms for early detection of fire locations, recognition of sun glint, and similar refinements. To improve satellite-based forest fire monitoring systems it is necessary to compare their efficiency. This will be the aim of our combined efforts in the near future.

This paper, based on the materials presented at the XI IBFRA Conference and GOFC/GOLD Workshop discusses the features of federal and regional satellite monitoring systems in Russia, compares their efficiency and results, and examines potential for their improvement.

1. The Federal Satellite-Based Forest Fire Monitoring System

The Federal GIS Center "Forest Fires" was organized within the framework of AFPS. This center receives satellite information about the forest fire situation in Russia daily and performs optimal control measures (Shchetinskii 1984; Korovin and Andreev 1988). The development of a satellite-based forest fire monitoring system was started in 1995 in co-operation with specialists from the International Forest Institute (IFI), the Center on Forest Ecology and Productivity (CFEP) of the Russian Academy of Science (RAS), the Institute of Solar-Terrestrial Physics (ISTP) of the Siberian Branch of RAS and the Space Research Institute (SRI RAS) (Bartalev et al. 1998; Belyaev et al. 1998; Abushenko et al. 2000).

The system provides forest services with the information obtained from processed AVHRR data to assist in management decisions. The main problems addressed by this system are the reception and fast processing of satellite data; integration of the processing results with the information obtained from other sources; and the fast supply of products to users. The system was designed to meet the following principal requirements, which determine its architecture and basic technologies:

- the main data flow – multispectral satellite data, allowing observation of the entire Russian territory several times a day (at the time of development, among civilian satellite systems, only the NOAA system of meteorological satellites met this requirement);
- supply of data for the entire territory of Russia (the information should be integrated from several centers of reception and processing of the satellite data);
- high speed of acquisition, processing and distribution of resulting data to users (the whole cycle should not exceed several hours, and in some cases – 20–30 minutes after raw data acquisition);
- integration of satellite data and processing results with the results of air and ground-based observations (the system should be integrated with the data acquisition and analysis system used);
- capability of obtaining promptly the results of processing of the satellite information for both the Central Air Base of AFPS and its regional bases, as well as various interested organizations (the information should be easily accessible for remote users);
- stability and, as far as possible, insensitivity of the data analysis and processing procedures in the system to observation conditions and regions (the system should eventually have several types of standard output information to be used by fire service specialists for decision making);
- flexibility, possibility of modification and extension (the system should have the capability of including additional information from other satellite systems, using additional data reception and processing centers, adding new procedures of data processing and representation);
- low operating cost (one of the most important requirements allowing for an easy control of the system).

In the following sections we describe some of the basic problems that were solved during the system development.

1.1. Prompt data exchange

One of the key points for the system under development is prompt data exchange, since, as can be seen from the above requirements, the system is distributed across Russia. To provide prompt data exchange, the system uses the Russian segment of the Internet. Such a choice imposes some restrictions on the amount of information transferred, and this factor was taken into account when planning data flows. At the same time, this choice opened several possibilities. First, leasing of dedicated trunk circuits could be avoided for data transfer between reception centers and specialized channels for system users (in this case, for a user it is sufficient to have access to the Internet). Second, the data transfer network is scaleable (i.e. the Internet data transfer speed in most cases can be easily increased for both the system elements and users). Also, no specialized end-user software is needed for getting access to the system data (users can use standard software for data reception by ftp or http protocols or by e-mail).

1.2. AUTOMATION OF THE DATA PROCESSING AND TRANSFER PROCESSES

Another significant element of the system development was the need to maximize the level of automation of the data processing and transfer processes. Based on these requirements, centers were selected so that the reception, processing, and exchange of satellite data could be organized with minimal expense. They are the center of ISTP SB RAS (http://ckm.iszf.irk.ru) and the center of SRI RAS (http://smis.iki.rssi.ru).

The satellite data acquisition areas of these centers cover almost the entire territory of Russia (except for Chukotka). Both centers are connected to the Internet through dedicated channels. They use the same basic software that allows complete automation of reception and processing of satellite data (Bukchin et al. 1994; Loupian et al. 1995). The data acquisition, processing and distribution system, whose principal scheme is shown in Figure 1, was initially based only on these two centers. Some key organizational features of this system will be discussed in greater detail.

1.3. TELEMETRY PROCESSING

All the data received from satellites is processed directly in the reception centers to avoid transfer of large volumes of information between different remote users. Whenever users need initial data for specialized processing that is not automatically performed by the system, they can get segments of initial data for the regions of interest. For products using data received by different receiving centers (for example, the cloud map over the territory of Russia), exchange of data segments or filtered data is organized between the centers. Experience of the recent years shows that users are generally more interested in the processed results than the initial data themselves. Therefore, the volume of raw data segment exchanges in the system is quite small.

Initial data segments and processed data are automatically transferred from the receiving and processing centers to servers of the AFPS air bases that are connected to the Internet through dedicated broad-band channels. This provides fast access to the data for users not only from the Central and Irkutsk air bases but also from

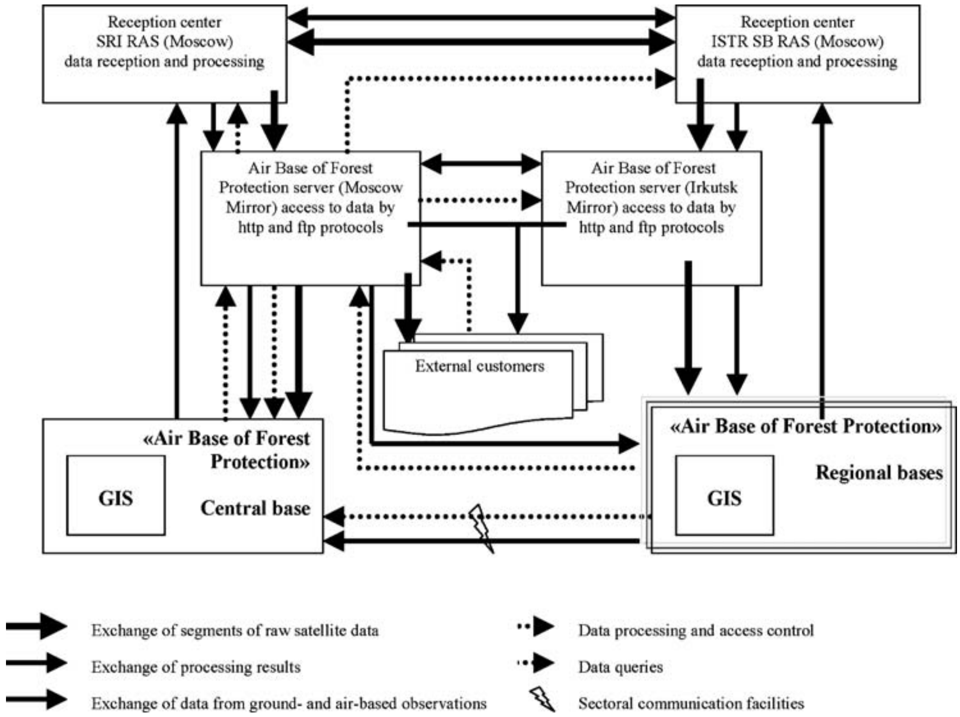

Figure 1. General operating scheme of the system for the reception, processing, and distribution of data in the Russian federal system of satellite monitoring of forest fires.

other regions. These servers are now installed at the center of the *Kosmos* network located in the SRI RAS and ISTP SB RAS, and the satellite data are accessible through local networks of these institutes as well.

It should be noted that in some cases satellite data are processed together with data from air and ground-based observations received by the Central and regional air bases. The exchange of this information with the satellite data receiving and processing centers is organized within the system.

1.4. Monitoring of the efficiency and operation of some system elements

To ensure the operation of the system as a whole, it was necessary to monitor its efficiency and the operation of its individual components. System monitoring was organized based on specialized technology developed in SRI RAS (Zakharov et al. 1997; Loupian et al. 1998). All information about the operation of system components is collected on the central server in Pushkino, where it can be analyzed by a manager. The manager can also control the data processing procedures, determining if the data for certain regions should be processed and transferred to GIS. These operations are performed through web-interfaces and interfaces directly to GIS of the Central Air Base. The manager can also register users on the server and provide them with access to different group of products.

1.5. ACCESS TO INFORMATION

The user can get access to the data either through the website of the AFPS (http://nffc.infospace.ru) or through ftp protocol. The latter method is preferred by air bases that use specialized GIS. Users not using specialized GIS can get and analyze the data through standard web interfaces. Both groups of users can get access to segments of initial data and to the set of standard products listed in the next section.

The users can send a request for information they need to the server. The system can perform specialized data processing for different regional users. Such processing is now performed for the Irkutsk and Novosibirsk air bases. For example, for the Irkutsk base the list of points with detected fires is compiled, and for the Novosibirsk base cloud maps are created.

1.6. DERIVED THEMATIC PRODUCTS

Cloud maps over the territory of Russia are compiled based on the data received at SRI RAS and ISTP SB RAS. To create a map, AVHRR channel 4 (IR) data are binned into 4 km gridcells. Shore lines, large water bodies and large fire markers according to the Central Air Base data are superimposed on this map along with the map of Russia divided into the regions monitored, in which satellite data are processed further. Daily cloud cover maps are generated during the entire fire season.

For regions with high fire danger, the full resolution data (1km/pixel) are processed further as soon as the information is received from satellites. This processing yields the following products represented in cartographic projection with superimposed coordinate grid, hydrological network, and names of settlements:

- *Result of fire detection by the Space Monitoring Center (SMC) algorithm.* These data have a relatively small volume and can be easily transferred even through a low-bit-rate switched channel.
- *Pseudocolor image based on AVHRR channels 3, 4, and 5* showing cloud cover or dense smoke, open surface, ”overheated” surface, and fires.
- *Image based on AVHRR channel 4 data* shows results of fire detection and marked regions of large fires according to the Central Air Base data. This product is used for the analysis of cloudiness, which not always can be fully identified by automatic processing.
- *Pseudocolor image based on AVHRR channels 1 and 2 and the results of fire detection by the SMC algorithm* showing cloud cover or dense smoke, open underlying surface, and fires.

- *Synthesized image of AVHRR channels 1 and 2 with the results of fire detection by the algorithm developed in the Lab of Remote Sensing of IFI,* showing cloud cover or dense smoke, open underlying surface, and fire zones. Detection is done only on daytime images. Nighttime images are shown as a synthesis of the AVHRR channels 3, 4 and 5. This product, similarly to the previous one, allows smoke from active fires to be observed.
- *Data converted into cartographic projection and saved in the ERDAS Imagine© 7.2 (LAN) format.* The data are complemented with maps of the solar elevation angle. They are used in the system if detailed processing with operator participation is needed.
- *List of detected hotspots with geographic coordinates.* The list is compiled from the results of detection by the two different algorithms. This list is then easily assimilated (imported) into GIS. These data are also used in the Internet-accessible information about regions where fires were observed based on satellite data.

A similar processing system is installed at ISTP SB RAS (Irkutsk). Both systems work in coordination and provide the Central Air Base and many regional bases of the Russian forest protection network with daily satellite data and the results of their processing. The experience of operating this system in 1997–1999 showed that the system was rather stable and rarely required human intervention. Addition of a new user to the system is possible with minimal additional expenses (such as expenses for Internet connection). In the future, this will allow the system to supply all the Air Bases with the information needed.

The system can be easily extended and modernized. Its architecture allows adding, whenever necessary, new procedures for analysis, processing and access to data, without interference with active components. It should be noted here that we do not describe the particular configuration of the system hardware because it is continuously updated and modernized.

1.7. SATELLITE DATA PROCESSING ALGORITHMS FOR MONITORING OF FOREST FIRES (CFEP/IFI)

A hotspot detection algorithm was developed at CFEP and IFI RAS for the federal-level forest fire monitoring system. The algorithm was based on the contextual approach developed by the Joint Research Centre of the European Commission (Li and Giglio 1999) and modified for areas covered by dense fire smoke.

To detect fires under dense smoke the approach with numerous thresholds based on a combined fire model is used. In this algorithm, potential fire pixels are grouped into several classes with different temperatures and albedos. Selection of these classes is justified by an analysis of errors of the first kind (missing target). To diminish the number of false alarms caused by the reflection of solar radiation from clouds, pixels with high albedo values in the visible channels are excluded from the fire class. At the same time, intense fires are accompanied by emissions of significant amounts of aerosol with high albedo values. In this case, some of the pixels not covered by smoke plume are passed through the standard albedo test. However, active fires are usually covered by smoke plume and therefore are not detected.

A criterion for the assessment of pixels with high values of albedo and brightness temperature in order to classify them as fires can be the presence of pixels classified as fires by the standard contextual procedures in the immediate vicinity. In this case, the requirement of diminishing the probability of omission error is fulfilled with the false alarm probability kept at the same level. The use of this method for hotspot detection leads to a significant increase in the detection probability under dense smoke conditions. The point is that the gain from using this criterion is especially noticeable for large fires. Taking into account that such fires cause 95% of all burnt areas, we should recognize that the effect from this criterion is rather high.

2. The Krasnoyarsk Regional System of Forest Monitoring From Space: Evaluation of Fire Danger

The Krasnoyarsk system of space-based monitoring of forests in the boreal zone of Siberia has been under development since 1994. In that year the receiving and processing station of High Resolution Picture Transmission (HRPT) from the NOAA/POES was installed at the V.N. Sukachev Institute of Forest in accordance with the agreement between NASA and RAS about co-operation within the "Mission to the Planet Earth" Project.

The station located in Krasnoyarsk allows reliable reception of information from three successful satellite passages, whose swath width is about 3000 km. Thus, the acquisition area covers the area from the Ural to the Khabarovskii Krai (42–138°E longitude and from Mongolia to the Arctic Ocean (48–80°N latitude) (Figure 2).

In spite of the low spatial resolution (1.1 km for AVHRR, 16 km for the High Resolution Infrared Radiation Sounder or HIRS, and 48 km for the Microwave Sounder Unit or MSU), the data from the NOAA satellites are useful for prompt forest fire monitoring and, in particular, for the evaluation and mapping of fire danger over vast territories, including boreal forests.

Data collection and dissemination are conducted continuously along the satellite path, and the data are automatically received and processed. Thematic processing of the data is performed in the following ways:

1. Digital images in the thermal range or in the multispectral combination of AVHRR channels, as well as the TOVS (TIROS Operational Vertical Sounder) data on pressure and wind velocity distribution at different altitudes allow the observer to follow the development of large-scale atmospheric activities, such as fronts, cyclones, anticyclones and wind storms.
2. AVHRR data in the visible and infrared ranges allow the observer to follow the dynamics of the Normalized Difference Vegetation Index (NDVI), as well as the water supply index. Analysis of NDVI data allows the classification of vegetation cover and the study of post-fire dynamics of damaged forest areas.

Figure 2. Acquisition area of the NOAA/HRPT receiving station in Krasnoyarsk.

3. The mid- and thermal IR AVHRR bands are used for active fire monitoring. AVHRR data processing algorithms are developed that enable the detection of thermally active points, and the determination of their geographic coordinates and areas. Small-size (subpixel) high-energy sources of thermal radiation are detected with the probability of 54%. The minimum experimental forest fire detected on an AVHRR image had the area of 6 ha.
4. Combination of three AVHRR channels (visible, near-IR, and thermal ones) enables the detection and representation of smoke plumes from active forest fires.
5. Information from the thermal AVHRR band allows the reconstruction of the temperature field of the visible surface. This information supplemented with the data from the low atmospheric layers about the dew point and precipitation (TOVS) serves the basis for the technology of the estimation, mapping, and short-term prediction of a fire danger index from weather conditions.
6. The visible and IR bands are also used for the calculation of snow and ice indices. These indices are used to separate active snow melting zones, to follow the dynamics of ice drift and freezing on big rivers.

Along with the conventional satellite data of reception and processing activities, the Krasnoyarsk center in recent years is undertaking attempts to solve the problem of prompt evaluation of fire danger (FH) from TOVS and AVHRR. The fire danger index characterizes the readiness of forest combustibles (FC) to ignition and maintenance of combustion. The decisive factor is the FC water content. The fire danger indices that are now in use in Russia were developed by V.G. Nesterov and then improved in the Leningrad Scientific Research Institute of Forestry (Vonskii et al. 1975). Calculation of these indices begins from the date of snow cover melt and continues to the end of the fire-*danger* season. The system for fire *danger* index estimation is based on information indirectly determining the FC water content, namely, the data of ground-based weather stations on the air temperature and the dew point. Two fire danger indices are used: PV-1 (humidity index) and PV-2 (floor humidity index). They are calculated by the following equations:

$$
\begin{aligned}
(PV-1)_n &= \{(PV-1)_{n-1} + t_{n-1}(t_{n-1} - \tau_{n-1})\}K_n,\\
(PV-2)_n &= \{(PV-2)_{n-1}\} \cdot K'_n + t_{n-1}(t_{n-1} - \tau_{n-1})K''_n,
\end{aligned}
\tag{1}
$$

where t is the air temperature at 01–03 p.m., in °C; τ is the dew point at 01–03 p.m., in °C; n is the day number; and K is the precipitation coefficient, which is equal to 1 on days with precipitation and 0 on all other days.

The precipitation index (K'') in Equation (1) is determined by the condition:

$K'' = 1$ at S < 1.6 mm and $K'' = 0$ at S$>$1.6 mm

where S_n is the total precipitation by the morning of the current day. If the total precipitation is less than 4.6 mm $K' = 1$. If the precipitation amount is greater than 0.5 mm and 4.6 mm for the coefficients K and K', respectively, the calculations are performed using precipitation tables (Vonskii et al. 1975). In the first approximation, these corrections can be represented in the form shown in Table I.

As the FC drying intensity is mostly determined by the combustible temperature (T_M) (Lykov 1968; Valendik et al. 1983), the water content is more correlated with K' than with the air temperature T_{air}, since the latter does not fully reflect the process of radiative heat exchange between FC and the ambient medium. In this regard the space-based methods of fire *danger* determination have an advantage, because they measure the radiative temperature of the underlying surface. In the Krasnoyarsk Center of Space Monitoring, the possibility of fire danger estimation from the sum of radiative temperatures was demonstrated based on archived data for 1996–2002.

In recent years no more than 60 weather stations, i.e. no more than two, on the average, per air group, are operated and supply information to the Krasnoyarsk AFPS air base. With such a number of weather stations for a territory of about 1.8 million square kilometers, it is impossible to evaluate and predict the spatial distribution of the fire danger index. The existing network of weather stations is insufficient for the need of creating large-scale maps of the fire danger in the region under study. Northern areas are almost not covered by observations, because of

TABLE I

Correction coefficients

Precipitation, mm	No or trace amounts	0.1–0.9	1.0–2.9	3.0–5.9	6.0–14.9	15.0–19.9	20.0 and more
Correction coefficient	1.0	0.8	0.6	0.4	0.2	0.1	0.0

the lack of weather stations there. The information from NOAA satellites is rather detailed and covers the whole area of interest. The coverage area, spatial resolution, and update rate fully satisfy the demands of the system for fire danger determination (Valendik et al. 1983; KOSDAN 1992).

The fire danger index of an area is determined by, besides the drying and watering factors, the local peculiarities of forest combustibles. To evaluate fire danger, it is necessary to take into account the FC structure and composition, as well as the peculiarities of a native zone, forest region, landscape, and to analyze statistical observations. The above factors form the basis for formation of the local scale of fire danger classes depending on the Nesterov index. The digital information from the NOAA satellites can be corrected by specialized software tools and complemented, for example, with the data on the local and seasonal FC peculiarities. Consequently, the resulting information in the form of a fire-danger GIS, can be more prompt and informative than that provided by the meteorological system of fire danger determination.

To calculate the fire danger index, it is necessary to know the surface temperature. Correlation analysis revealed a close correlation between the temperature measured at ground-based weather stations and the radiative temperature at the same points obtained by AVHRR. The correlation coefficient is $r = 0.75$. The differences caused by different measurement time show themselves as systematic deviation (5–10 °C), which can be taken into account in calculations.

The temperature under the cloud layer (invisible for the AVHRR thermal channel) can be retrieved based on TOVS microwave data. Unlike the AVHRR IR channels, TOVS allows temperature retrieval in regions covered by clouds. It is possible to retrieve vertical profiles of 15 parameters (including the air temperature and dew point) at 600 points distributed over the area of the satellite swath. One AVHRR scene covering the area of 1000×1000 km^2 corresponds to 150 TOVS footprints. In terms of coverage and resolution, TOVS is also a source of complementary information of the weather station data. In this case, there also exists a close correlation between the TOVS data on the air temperature and the data of weather stations. On the average, for all weather stations in the Krasnoyarkii Krai the correlation coefficient is $r = 0.88$. The systematic deviation for the air temperature is 7.9 °C. It should be noted that in this case the deviation is also mostly caused by different measurement times. Thus, TOVS data can be justifiably used to restore temperatures under the cloud layer as an additional or alternative source of information.

Another parameter needed for the determination of fire danger of forest areas is dew point. TOVS allows the retrieval of the vertical dew point profile. It was found that the correlation coefficient between the satellite data for the surface layer and measurements at weather stations is $r = 0.77$, and with a mean systematic deviation for the dew point is 3.8 °C.

The data on precipitation needed for estimation of the Nesterov fire danger index can be taken from databases of weather stations.

In our procedure of fire danger determination a correction is introduced in accordance with the correction coefficients developed by Zhdanko and Gritsenko and tested with voluminous statistical material (Zhdanko and Gritsenko 1980).

As a result of studies performed, it was concluded that satellite data can be used as initial information for the evaluation of fire danger index, at least for forest areas of the Krasnoyarskii Krai. An algorithm was developed to take into account the dynamics of diurnal variation of the weather parameters, and a technique was obtained to extrapolate the raster microwave TOVS data to the whole territory of the Krasnoyarskii Krai.

The method for generating fire danger maps consists of three related stages. The first stage (preliminary processing) includes reception and recording of the satellite signal, calibration of the data, georeferencing and sectorization (selection of an AVHRR scene and the combination of channels), as well as conversion of the selected scene into a preset geographic projection. For the calculation of the fire danger index data of three AVHRR channels are used: channels 1 and 2 (visible and near-IR), carrying the information about the surface albedo and channel 5 (thermal band). The temperature field of the visible surface is retrieved from the image in channel 5. The combination of the visible and near-IR channels allows the areas covered by clouds and water surfaces to be excluded.

The second stage involves computations. A program suite was developed for co-locating a series of images and calculating the fire danger index at any image pixel.

The third stage is the processing of the result with the application of GIS technology using ArcView© 3.2. The classes of fire danger are separated based on the preset ranges of values of the fire danger index (Figure 3). The GIS processing technology allows the maps of fire danger, based on the information about weather conditions, to be complemented with the information about forest combustibles, after which it becomes possible to estimate energy parameters of forest fires (Ponomarev and Sukhinin 2000). This information is needed for planning fire prevention.

The fire danger index is calculated according to the Nesterov equation traditionally used in Russia (1):

$$\Gamma_{ij} = \sum\nolimits_i a_i \xi_i \sum\nolimits_j t_{ij}(t_{ij} - \tau_{ij})$$

where Γ_{ij} is the fire danger index, τ is the dew point (°C) according to the TOVS data, t is brightness temperature

$$a = \left(\frac{A_{3a} - A_1}{A_{3a} + A_1} \cdot \frac{A_2 + A_1}{A_2 - A_1} \right)$$

of the visible surface (°C) from AVHRR, ξ is the precipitation coefficient from TOVS data and the GIS Meteorological database of weather stations, A_n are the

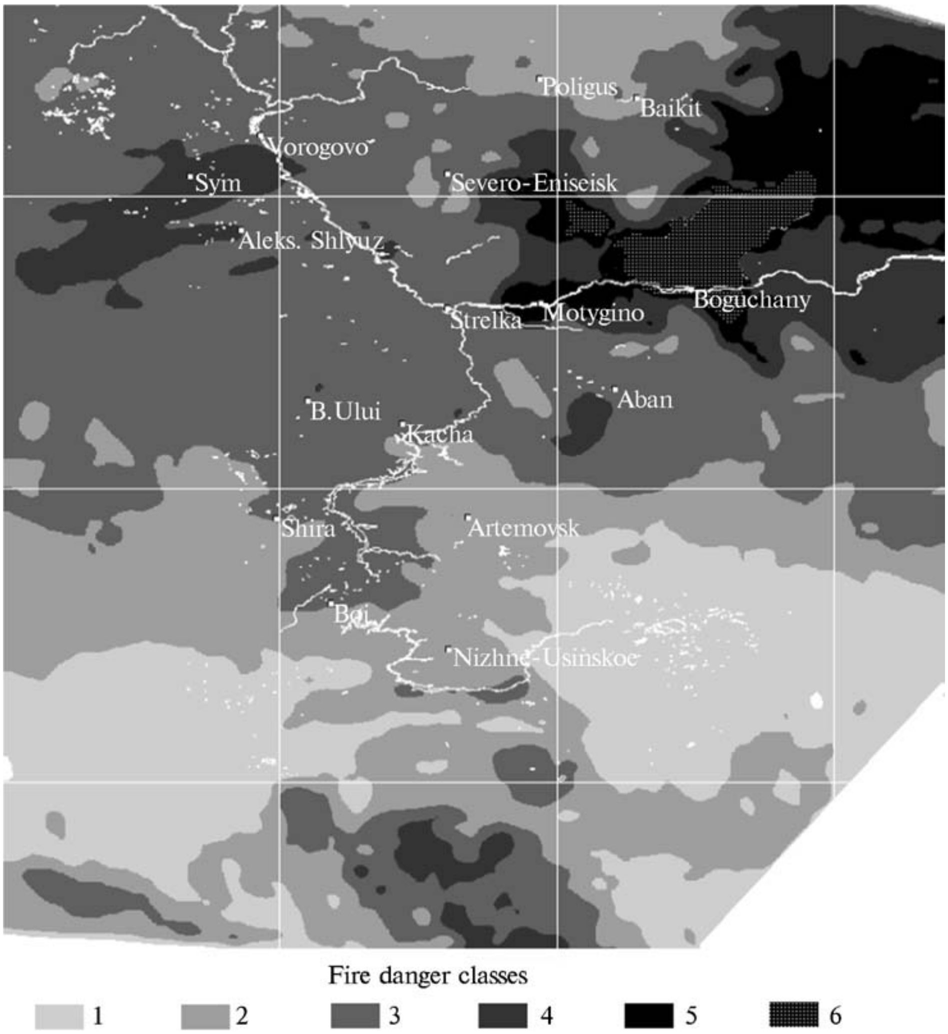

Figure 3. Map of the fire danger index over the territory of the Krasnoyarskii Krai for July 24 of 1996.

values of AVHRR channels 1, 2, and 3a on NOAA-16. The calculations are performed at every image pixel (i) every day (j) of the fire-danger period.

To restore the temperature field at the area covered by clouds TOVS data were used. But since they are irregular, the temperature at any surface point was calculated by the method based on piecewise linear approximation, in which the surface determined by a function is approximated by a piecewise linear surface consisting of triangles. For this purpose, a pattern of non-overlapping triangles is drawn on the plane (x, y). The projection of every point onto the plane (x, y) belongs to only one triangle face, and the value of the function $f(x, y)$ is approximated by a piecewise linear function taking preset values at points of the reference set (Shikin et al. 1993). The triangulation process consists of creating a network of non-overlapping triangles with vertices at preset points. These reference points were the locations of the TOVS footprints and the weather stations.

This procedure was done using triangulation. The cross section of the obtained piecewise linear surface gives an isoline of a parameter. Linear extrapolation by three neighboring points – vertices of a triangle face including this point – allows the parameter value to be reconstructed at any preset location. The technique described allowed the reconstruction of the spatial pattern based on both TOVS and weather station data. Similar method can be also used for the interpolation of precipitation data from weather stations.

The derived maps of the distribution of cumulative temperature formed the basis for the compilation of a fire danger GIS. The ArcView© 3.2 software allows this information to be complemented with a geographic database, forest map, and territorial and administrative zoning. An example of the map (July 1996) is shown in Fig.3. Five traditional fire danger classes were separated according to the FH index value, and the sixth class for the area of extreme fire danger was additionally introduced in the Angara river basin. In this region 72 forest fires burned for three days.

The proposed technology allows prompt compilation of maps of the spatial distribution of the FH index for vast regions, in particular for areas not covered by information of weather services. The spatial resolution of such maps is much higher.

Table II presents the results of analyzing the correlation between the FH index derived from NOAA satellite information and the Nesterov FH index calculated from weather station data. The high correlation coefficients for the Angarskaya and Northern groups of areas in 1996 can be explained by a stable anticyclone that prevailed over this territory for the period of observations. Thus, the remote sensing methods are most efficient whenever fast evaluation of fire danger is needed during extreme fire danger seasons.

3. The Irkutsk Regional Space Monitoring System: Fire Detection Algorithms and GIS Technologies

The system for receiving and preprocessing of data from NOAA satellites was installed at the Institute of Solar-Terrestrial Physics SB RAS in 1993. The monitoring of forest fires with the use of satellite technologies has been conducted at the Remote Sensing Center (RSC) since 1994. ISTP took part in development of space monitoring systems at the federal and regional levels (Abushenko et al. 1998a). Here we focus on the regional-level system. The Irkutsk regional system has goals identical with those of the federal system and solves almost identical problems. The two systems, however, differ in techniques for processing satellite information to detect

TABLE II
Correlation coefficients calculated based on measurements in the fire period of 1996

Groups of areas	Weather station	Correlation coefficient
Angarskaya	Strelka	0.87
	Motygino	0.71
	Boguchany	0.98
	Aban	0.91
Northern	Vorogovo	0.89
	Aleksandrovskii Shlyuz	0.96
	Severo-Eniseisk	0.95
	Poligus	0.98
	Baikit	0.99
	Vanavara	0.92
Southern	B.Ului	0.85
	Kacha	0.88
	Artemovsk	0.84
	Beya	0.65
	Nizhne-Usinskoe	0.86

and record forest fires, and in formats and methods of the representation of the processing results. Satellite-based fire detection methods did not immediately receive a positive response from specialized forest fire management agencies, primarily due to the perceived reliability of the satellite information. Over the seven years of experience, however, RSC has continuously developed efficient algorithms for the processing of satellite data, one of which is the combined fire detection method. This method consists of both automatic decoding and interactive analysis.

The first automated satellite-based forest fire detection algorithms were developed at RSC in 1995. Their testing revealed both merits and deficiencies. Initially, threshold-based algorithms were based on the difference in spectral properties between fires and other objects (Abushenko et al. 1998b; Abushenko et al. 1999b) . With this approach, there was a problem with false alarms caused by the reflection of solar radiation from clouds in AVHRR channel 3.

The improved algorithm follows a two-stage scheme. First, the areas of potential fires and other information are separated with a standard discriminator (Swain and Davis 1978). At the second stage, (for further detailed processing) a complex separating surface, predescribed by potential functions with a given training sample is used. With this scheme, the form of the potential function used at the second stage is simplified at the first stage, and thus the efficiency increases and the computational time is reduced.

The separating function is determined at the first stage based on the analysis of spectral radiance in AVHRR channels from forest fires and objects with similar spectral characteristics referred to as false fires or noise. As a sample of spectral characteristics of fires and noise, satellite data from the Irkutsk Region from 1996–1999 were used, along with the data on fires in the Far East and in Southern Russia from 1998. The sampled spectral characteristics of noise were complemented with the information about the most characteristic cases of observation of such objects – cloudiness with high brightness temperature in channel 3 due to reflection, optically thin and low clouds above the warm surface, overheated surface areas in the zone of dry steppes and deserts, and sun glints. The problem was solved with three exponential separating functions (Figure 4):

1) $T_p = a_1 * \exp(b_1 A_1)$
2) $T_p = a_2 * \exp(b_2 A_1)$
3) $T_p = a_3 * exp(b_3 A_1)$

where T_p is the temperature determined as:

$$T_p = F(B_p, \nu_3)$$

where $B_p = B_3 - B_3(T_4)$, B_3 is the radiance in AVHRR channel 3, $B_3 = F(T_4, \nu_3)$ is the radiance at the channel 3 frequency calculated from the temperature in

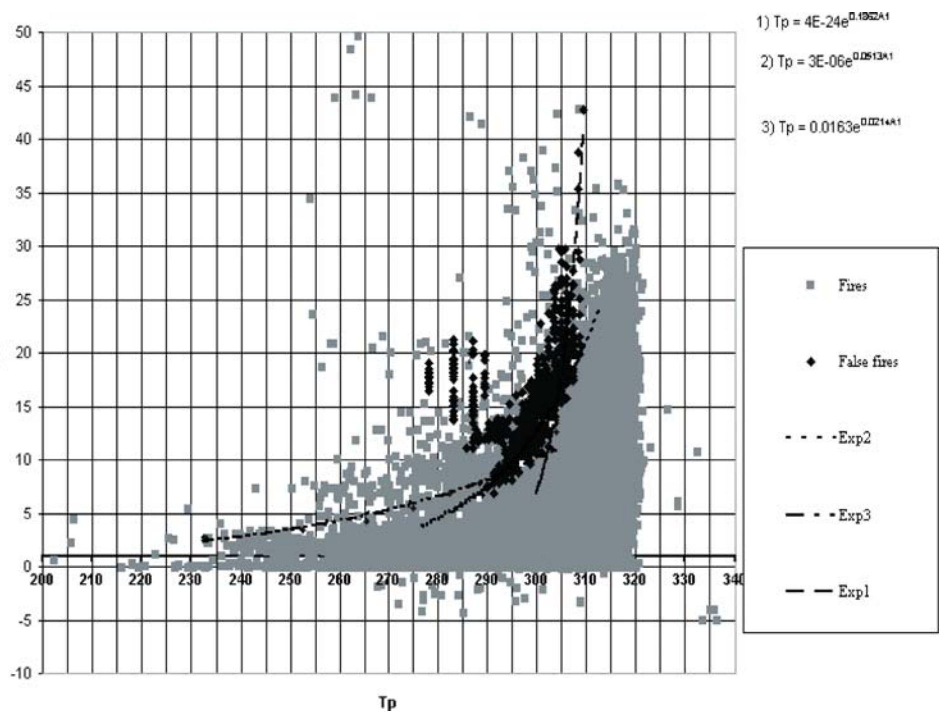

Figure 4. Fires, false alarms and exponential separating functions.

channel 4, ν_3 is the wave number of channel 3, F is the Planck function, $a_1 - a_3$ and $b_1 - b_3$ are coefficients, A_1 is the equivalent albedo in the AVHRR channel 1.

Additional criteria for separation of potential fires are $A_1 < 35\%$, $T_4 > 265$ K for rough separation of cloudy areas, as well as $(T_3 - aT_4 - b(T_4 - T_5)) > 4$K for separation of hot surfaces. Sun glints are separated using the criterion $(A_1 - A_2) < 0$ (only in the regions where glints are geometrically possible).

As a result, from 70 to 100% of noise is rejected at the first stage. The missed true fires in this case amount to about 4%. Some areas of low and, consequently, warm St and As clouds with low optical thickness do not get rejected, along with small inhomogeneities in the zones with surface temperature close to the saturation temperature of channel 3. Missed fires correspond to areas of difficult weather conditions characterized by the presence of thin clouds or large amounts of smoke. In addition, weak fires at a low-temperature background are sometimes missed.

At the second stage, processing by the method of potential functions is applied. The input parameters for the algorithm are data of the five AVHRR channels, and the contrast near potential fires in the channels 2, 3 and 4. Thus, the eight-dimensional space of indices is used. The decision function is constructed based on the fire sample determined by a human operator with the iterative learning procedure having the form:

$$d(x) = a_1 \exp\left\{-c||x - x_1||^2\right\} + a_2 \exp\left\{-c||x - x_2||^2\right\} + \cdots + a_k \exp\left\{-c||x - x_k||^2\right\}$$

where x is a pattern to be recognized, x_i, i = 1, 2,..., k, are patterns recognized during the learning process, a_i, $i = 1, 2, \ldots$, k, are numerical coefficients equal to 1 if the pattern x_i is recognized as a fire or, otherwise, –1, c is a positive constant, and $||x - x_i||$ is the norm of the vector $(x - x_i)$. The function $d(x)$ is positive if x is a fire and negative otherwise.

Thus, for a fire:

$$d(x) > 0 \tag{2}$$

To assess the accuracy of this algorithm, its results were compared with those provided by other techniques. To obtain numerical characteristics, 26 AVHRR test scenes, each about 500 × 500 km in size, were used. They were sampled over various geographic regions including Nizhnyaya Volga, Northern Caucasus, Northwestern Russia, Western and Eastern Siberia, Yakutiya, and the Far East. The sampling was performed for different times of day (daytime, nighttime) and different seasons (spring, summer, fall). 860 fire pixels were identified on these images using expert evaluation. The results of the comparison are given in Table III. It is obvious from the analysis of these results that the most efficient algorithm is based on potential functions, which missed only 6% of fire pixels and mis-interpreted about 10% of noise pixels as compared to the total number of fire pixels. The second most efficient algorithm is the multistage threshold algorithm. In spite of the fact that it misses 10% more fire pixels than the contextual algorithm, the stability of the multistage

TABLE III

Results of inter-comparison of RSC algorithm performance with other algorithms

	Method of potential functions[a]		Contextual algorithm[b]		Multi-step method[c]	
	Number of pixels	Percent from total	Number of pixels	Percent from total	Number of pixels	Percent from total
Missed fires pixels	54	6%	246	28%	330	38%
Noise pixel instead of fires	78	9%	414	48%	94	10%

[a]Algorithm developed by the RSC ISTP SB RAS.
[b]Algorithm developed by Flasse and Ceccato (1996).
[c]Algorithm developed by Abushenko et al. (1998b).

threshold algorithm to noise separation is almost five times higher than that of the potential functions method.

From this study, we conclude that: 1) the main indices used for fire detection based on AVHRR data are widely variable in Eastern Siberia; 2) application of simple linear separating functions in threshold classification algorithms is inefficient (in this case, the number of fires missed by different threshold methods can reach 50–80% depending on various condition); and 3) the fire detection algorithm based on the method of potential functions is the most efficient of those considered.

RSC successfully uses the specialized software for processing of satellite information in order to detect forest fires. Besides automatic detection of forest fires (the algorithm is described above), it also includes interactive procedures for more accurate determination and correction of geographic coordinates, and filtering out false fires caused by random noise on the image. This software allows an operator to perform visual detection of low-intensity fires, which were missed by the algorithm, based on these criteria:

- positive temperature contrast of a pixel or small group of pixels (cluster) with the background in channel 3;
- absence of temperature contrast of this pixel with the background in channel 4;
- with the low temperature contrast at the considered point in channel 4, the temperature in channel 3 should be equal to the sensor's saturation temperature (322K), and the size of a fire cluster should be larger than 2–3 pixels;
- no increased brightness in channel 1;
- no increased temperature in channel 4 within the cluster and no identical cluster shape in channels 3 and 4.

To separate noise, whose main manifestation is the high value of brightness temperature, a regression relation between T_3, T_4, and T_5 was established. Having the following form, it is a discriminator separating the classes of fires and the corresponding noise in the IR spectral region:

$$T_3 = aT_4 + b(T_4 - T_5) + C$$

From Equation (2), the classification index was determined to separate fire and noise, namely,

$$T_3 - aT_4 - b(T_4 - T_5) > C \tag{3}$$

where $a = 1, b = 3, C = 4\text{K}$.

Analysis of the data for testing areas showed good results of separation between fire and noise. For noise the values C of the expression (3) varied from 4 to −15, while for fire they are from 0 to 15 and higher. The classes overlap in the range from 0 to 4, which, according to observations, corresponds to weak, small fires and fires at the dying stage.

For more efficient separation of noise, whose main indicator is high reflectivity, it was proposed to use the ratio of the radiances in AVHRR channels 3 (B_3) and 1 (B_1):

$$Ai = B_3/B_1 \tag{4}$$

The physical meaning of this parameter is based on the fact that some correlation exists between the reflectivity in the visible and mid-IR regions for noise objects. This index can also be used with high efficiency for the identification of smoke plumes, since the presence of smoke aerosols very strongly affects radiation scattering in the visible spectral region and has almost no effect in the mid-IR region. As a result, in the image of the Ai index, the objects with high reflectivity and aerosol smoke plumes have increased brightness, while fires are characterized by low brightness. The absolute value of the parameter Ai cannot be used for distinguishing fires and noise, since it varies rather widely depending on the characteristics of atmospheric transmittance. Therefore, this index is used only for visual analysis.

Representation of the information about forest fires, their area and dynamic characteristics imposes certain requirements onto satellite-derived products (promptness, information content, reliability, etc.) and the forms of representation of these products in an integrated decision-making system (Abushenko et al. 2002). Taking into account the spatial context and the suite of satellite-based products and data from other measurement tools (with digital representation of information), GIS technology can be a valuable tool for developing such a system. The GIS technology allows inclusion of different types of data from numerous sources, keeping, whenever necessary, their spatial orientation.

The MapInfo package of the GIS center of the Irkutsk Scientific Center SB RAS was used as the underlying software. The GIS is organized in such a way that with a few simple operations the user can update the thematic layer obtained from real-time satellite-, air- or ground-based information. The 1:1000000 digital maps provided by “DATA+” (www.dataplus.ru) are used as the topographic basis. The main thematic layer is a vector layer of the block forestry network in the Northern areas of the Irkutsk Region developed at ISTP.

To import satellite-based information into GIS, the user requests the results from ISTP website (http://ckm.iszf.irk.ru) in GIS file format. With this GIS, the database of detected forest fires was compiled based on the data of satellite observations conducted by ISTP SB RAS for 1997–2001 at the territory of the eastern part of Russia. Fire locations are represented as polygon-type objects containing the information about spatio-temporal characteristics of fires and physical values of AVHRR measurements.

The GIS “Forest Fires in the Irkutsk Region” allows implementation of the information about forest fires obtained by the ground-based and airborne observation methods and qualitative and quantitative analysis of the satellite and ground-based information, as well as compilation of reports. This GIS database is used by the Irkutsk AFPS Air Base and its regional departments, as well as administrative bodies and forest divisions of the Bratsk, Ist-Ilimsk, Nizhneilimsk, Ust-Kut districts of the Irkutsk Region. The experience of using this GIS has shown a significant increase in information content and improved visualization of remote sensing data both in real-time mode and in data analysis.

4. The Tomsk Regional System: Efficiency of Early Detection of Forest Fires

In the Tomsk Region, forest fire management agencies registered 1185 forest fires with the total area of more than 60000 ha in the period from 1998 to 2000 (Figure 5). Space monitoring of forest fires in this region has been performed by the Institute of Atmospheric Optics SB RAS since 1998 with (a) SCANEX digital satellite receiving station for NOAA/HRPT (Bukchin et al. 1992); (b) a wide set of standard and original software tools for processing satellite data; and (c) theoretical and algorithmic results needed for the solution of the problem and multi-year experience in interpretation of satellite data.

The system of space monitoring of fires was developed taking into account both foreign (see, for example, review in Kaufman and Justice 1998) and Russian (Shikin et al. 1993; Kondranin and Ovchinnikova 1995; Zherebtsov et al. 1995; Abushenko et al. 1999a; Sukhinin 1996; Sukhinin et al. 1999a; Sukhinin et al. 1999b; Abushenko et al. 1998a) experience accumulated in this field. The scheme of space monitoring of forest fires includes the following main stages:

1. reception of digital satellite information;
2. data preprocessing, including calculation of geographic reference based on the well-known SGP4 program (Hoots and Roehrich 1988) and orbital data TLE-NORAD Two-Line Elements Set accessible through the Internet at (http://celestrak.com/NORAD/elements/noaa.txt);
3. improvement of geolocation in the semi-automatic mode by reference points and contour hydrographic lines;

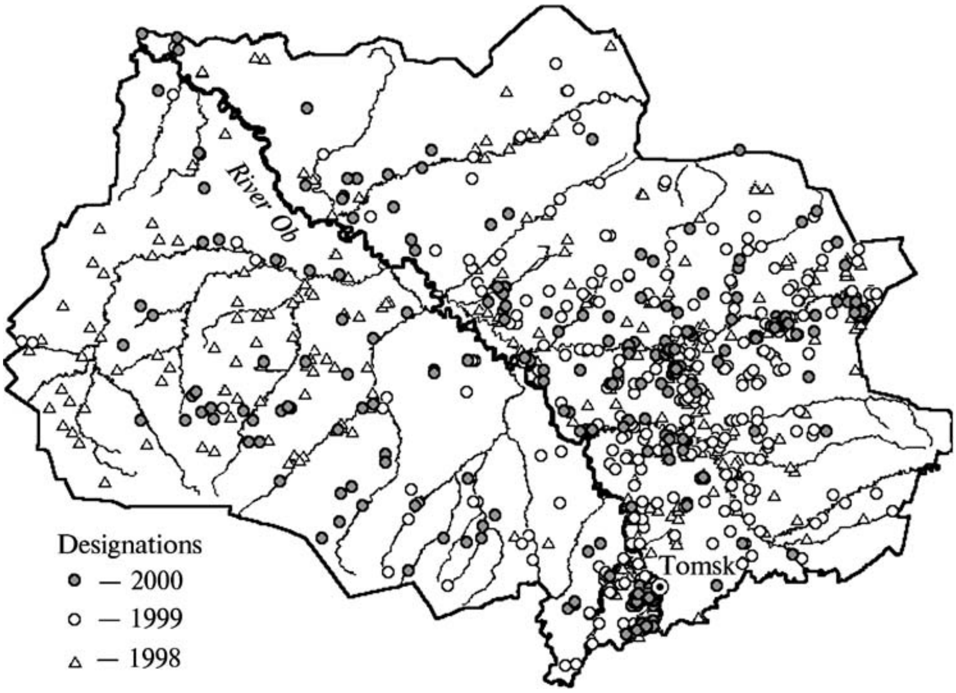

Figure 5. Map of forest fires over the Tomsk Region in 1998–2000 (with contours of the biggest rivers).

4. automatic thematic decoding of AVHRR data with simultaneous use of two essentially different algorithms for the detection of high-temperature anomalies on the underlying surface (in order to improve the reliability of detection results);
5. automatic rejection of false alarms (sun glints) and stationary industrial thermal objects;
6. generation of reports (in text and graphical formats) and their uploading onto an FTP server.

The results of the automatic processing of satellite images and the quality of false alarm rejection are monitored by an operator. To increase the reliability of detection of subpixel fires, an automated analysis of the time series of previous satellite images was used. The organization of the system of space monitoring of forest fires in the Tomsk Region is described in more detail in (Afonin et al. 2000).

Here we present an analysis of the efficiency of application of satellite technologies in 1998–2000 to real-time detection of forest fires at the territory of the Tomsk Region. These issues have been considered elsewhere in the literature (e.g., Abushenko et al. 1998b; Zherebtsov et al. 1995; Sukhinin et al. 1999a; and in more detail, in Boles and Verbyla 2000; Afonin and Belov 2002). Of particular importance here is the efficiency of early detection of fires (as compared to the data of regional forest fire management agencies), since this is the principal determinant of the value of the satellite information for these agencies.

A combined analysis of the results of space monitoring was done in the study area for May–September 1998–2000. Fire reports from the Tomsk AFPS in these periods were used as reference information. When comparing the satellite information with the reference data we considered: 1) the geographic coordinates (latitude and longitude) supplemented with the azimuth and the distance between the fire and the flight location; 2) the date and time of fire detection (T_{det}), localization (T_{loc}) and extinction (T_{liq}); and 3) fire area at the time of its detection (S_{det}) and extinction (S_{liq}).

For statistical processing of data and generating histograms, the variability range of the fire area S was divided into 14 subranges, and the range of fire lifetime [$T_{\text{det},}$ T_{liq}] was divided into 11 subranges. To evaluate the efficiency of early detection of forest fires from satellites, the fire lifetime was extended up to [$T_{0,} T_{\text{liq}}$], where $T_0 = T_{\text{liq}} – d\text{T}$ (dT depends on S_{det}). In addition, in the course of executing some program blocks, fire area S(T) at the time T of space monitoring was estimated. For each satellite image high temperature anomalies detected from the satellite data were mapped with the use of geographic coordinates. A map of locations of fires, for which the imaging time falls in the interval [$T_{0,} T_{\text{liq}}$] (the maximum number – 75 fires), was also compiled. These two maps were compared, and the coinciding pairs of objects were selected by the given spatial criterion with allowance for their size and the probability of a fire on the image, which was assumed equal to 1 in the interval [$T_{\text{det}}, T_{\text{liq}}$] and decreasing towards zero at $T \to T_0$ or $T \to T_{\text{liq}}$.

To obtain a general perspective on forest fires in the Tomsk Region, Figures 5 and 6 give the data on some fire characteristics. The map of the spatial distribution of fires at the territory (Figure 5) reflects the fact that most of the forest area is exposed to potential fire danger. The histograms of the fire distribution by area S_{liq} and by lifetime [T_{det}, T_{liq}] are shown in Figures 6a and b respectively.

The distributions shown in Figure 6 have relatively small (less than 6–7%) annual fluctuations, although in year 2000, very large (maximum area of 180 ha) and long fires were absent. From the data in Figure 6 it follows that the number of subpixel fires with the area less than 1 ha is, on the average, about 60%, while the number of short (lifetime less than 12 h) fires exceeds, on the average, 50%. Thus, we can expect that more than 50% of fires have a low probability of detection from space.

Table IV gives the results of space monitoring of forest fires in the Tomsk Region for every month in the interval 1998–2000. It includes the number of fires detected by forest fire control services ($\mathbf{NF}_{\sum}$); the monthly mean amount of clouds, that is, the size of the territory inaccessible for space monitoring of the underlying surface; the total efficiency of monitoring – the total number of forest fires detected from space ($\mathbf{NF}_{\text{det}}$); and the efficiency of early fire detection (EFD) – the number of fires detected from space earlier then they were found by the forest fire control services ($\mathbf{NF}_1$). Table IV shows that the efficiency of monitoring in different years ranges from 24 to 40%. A total of 367 fires (about 31% of their total number) were

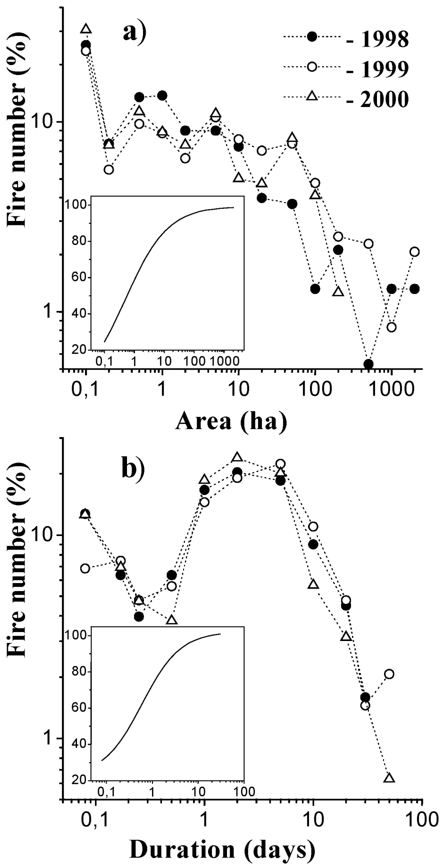

Figure 6. Frequency distribution of fires by area (a) and duration (b) with the corresponding integral functions inserted.

detected from space during the fire seasons of 1998–2000. The efficiency of early fire detection ranges within 11–18% (162 fires) or, on the average for 3 years, equals about 14%.

In efficiency estimates, it is worth taking into account that some fires (or observation conditions) had the characteristics making their detection from space almost impossible. This is connected with the following reasons: (a) fire lifetime was so short that the interval [T_{det}, T_{liq}] fell between consecutive images; (b) the distance between fires (with overlapping lifetimes) was less than 2 km, that is, they could not be separated in space images; and (c) fire was covered by dense clouds for the entire interval [$T_{det,}$ T_{liq}].

In Table IV the column "Total" in parenthesis presents the number of such fires for every year (15–25% of the total number of fires), although this value is, in our opinion, seriously underestimated (this follows, at least, from the fact that such a

TABLE IV

Final results of space monitoring of fires in 1998–2000

Month	May	June	July	August	September	Total
			1998			
$NF_{\sum}$	24	32	175	147	–	378 (−87)
Cloudiness	34.6%	49.3%	20.1%	46.4%	–	
NF_{det}	6	2	38	51	–	97
NF_1	5	1	11	25	–	42
			1999			
$NF_{\sum}$	60	31	199	132	60	482 (−80)
Cloudiness	45.7%	55.6%	28.5%	49.6%	61.8%	
NF_{det}	39	9	72	51	22	193
NF_1	20	0	23	33	10	86
			2000			
$NF_{\sum}$	47	93	110	49	19	318(−57)
Cloudiness	59.0%	35.5%	46.9%	48.6%	70.4%	
NF_{det}	16	25	26	8	2	77
NF_1	6	18	9	1	0	34

factor preventing detection of small fires as forest canopy in the zone of development of 96% of the fires was ignored here). If these fires not detectable from space are subtracted from the total number, the mean efficiency of space monitoring increases to 39%, and the mean efficiency of early detection reaches 17%.

From Table IV, we can also analyze how the efficiency of space monitoring depends on the fire size. Figure 7, shows a) the histogram of the distribution of the early detection efficiency over the fire area S_{det} and b) the dependence of the total efficiency of space monitoring on the area S_{liq}. Using the data of Figure 7b, we can separate the following estimates of the space monitoring efficiency depending on the fire area: up to 20% for S less than 1 ha, 40–55% for $S \approx$ 5–10 ha and 80–100% for S larger than 50 ha. These data agree well with the conclusions of (Zherebtsov et al. 1995). The minimal size of forest fires detected from space is about 0.1–0.2 ha, and such fires are detected with the probability of about 10%.

From the experience of forest fire management agencies, it is known that a ground fire with area less than 5 ha can be extinguished with high probability. Figure 7a shows the rather high (greater than 20%) efficiency of early detection with S as low as 2 ha, which increases up to 30–45% for $S \approx 5$ ha. Thus, the satellite information can be used rather efficiently for early detection of fires at the early stage of their development, when their extinction is not very costly.

The information content of satellite data in monitoring forest fires at different times of the day may also be useful. All the monitoring results were divided by

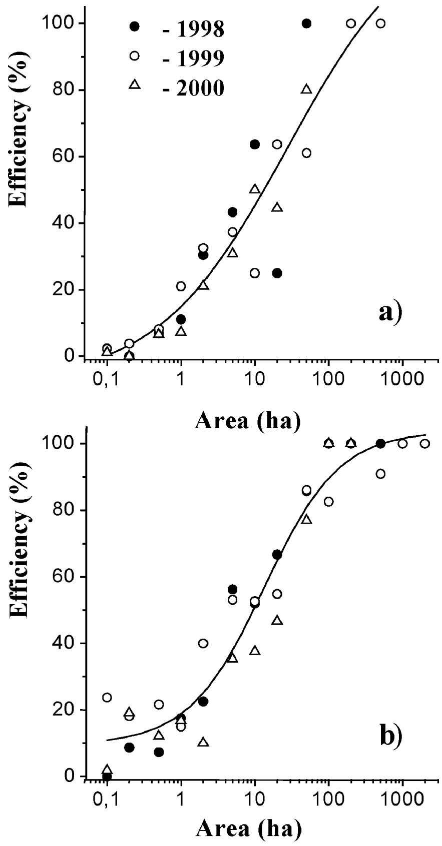

Figure 7. Efficiency of earlier detection of fires from satellites (a) and total efficiency of space monitoring of forest fires (b) as functions of the fire area.

the types of satellites and orbits (a.m. and p.m.). This division is dictated by the fact that there are space-based monitoring schemes that use only p.m. images, such as the daytime image of the NOAA-14/AVHRR. This approach is caused by the obvious circumstance that p.m. images are most informative and close in time to the appearance of new fires and the activation of already existing ones.

The data in Table V give an insight into the efficiency of AVHRR monitoring of fires depending on the time of a day. It is rather low for morning images and significantly (2–3 times) higher for afternoon images. However, it follows from Table V that the use of the information of only one (even the most informative) image leads to 20–25% decrease in the efficiency of space monitoring, while the efficiency of early detection decreases 1.5–2 times.

The column “Total” of Table VI gives the efficiency of space monitoring with the use of only afternoon images. Hence it follows that the afternoon images provide for 95% of the total efficiency of monitoring and more than 85% of the efficiency

TABLE V

Results of space monitoring of fires in different period of a day

Orbits	AM			PM			
satellites	NOAA-12	NOAA-14	NOAA-15	NOAA-12	NOAA-14	NOAA-15	Total
Time	08.2–10.0	04.9–06.8	–	18.5–20.2	15.1–16.8	–	
N_{IMG}	91	93	–	86	83	–	
NF_{det}	24.7%	34.0%	–	76.3%	80.4%	–	94.8%
NF_1	9.3%	23.3%	–	34.9%	72.1%	–	85.7%
				1999			
Time	07.9–09.6	05.7–07.5	–	18.1–19.8	15.7–17.6	20.0–21.7	
N_{IMG}	150	148	–	153	152	153	
NF_{det}	22.2%	23.7%	–	74.7%	67.0%	57.7%	96.4%
NF_1	19.8%	14.0%	–	54.7%	52.3%	48.8%	91.9%
				2000			
Time	07.5–09.8	06.4–09.0	09.9–12.0	17.7–19.8	16.3–18.3	20.0–21.9	
N_{IMG}	121	132	81	126	141	83	
NF_{det}	13.0%	15.6%	26.0%	66.2%	75.3%	46.8%	94.8%
NF_1	5.9%	0.0%	32.4%	55.9%	55.9%	35.3%	85.3%

Notes:

1) Time means the satellite reception period in local time hours.

2) N_{img} is the number of satellite images.

3) Total efficiency of space monitoring of forest fires (NF_{det}) and efficiency of early detection (NF_1) are given in percent with respect to the total annual indices (see Table 4.1).

of early detection. However, in spite of the high information content of afternoon images, rejection of morning images still leads to the loss of some useful information and a marked decrease in the efficiency of early detection. Consequently, only the AVHRR monitoring including processing of all satellite images regardless of the time of a day provides the maximum efficiency of monitoring, observation of fire dynamics and the state of cloudiness in the zone of fire development.

Two well-known problems affect the quality of space monitoring of forest fires: sun glint artifacts and georeferencing of events. In the Tomsk Region there are hundreds of rivers and relatively small water bodies, and at some observation geometries these can act as sources of sun glints in the satellite images, generating false alarms. However a large proportion of the fires in the Tomsk Region occur in the immediate proximity of rivers and water bodies. In this region, therefore, the problem to be solved is not the simple rejection of sun glints, but also the separation of neighboring glints and fires, whose area may not exceed a few pixels. The maximum number of glint situations at the territory of the Tomsk Region (with no clouds) as estimated for the fire-danger seasons of 1998–2000 is about 5–10% of the total number of images.

TABLE VI
Errors in georeferencing AVHRR images

Satellite	NOAA-12			NOAA-14			NOAA-15			TLE
	y	*x*	*D*	*y*	*x*	*D*	*y*	*x*	*D*	
					1998					
Mean	0.4	1.7	4.2	1.1	1.8	4.5	–	–	–	0.17
RMS	1.1	4.4	2.5	3.9	2.2	2.1	–	–	–	–
Max	−4	−10	10.2	12	8	13.0	–	–	–	0.42
					1999					
Mean	0.3	1.7	3.6	0.4	1.7	4.5	0.1	2.5	4.0	1.78
RMS	2.9	2.3	1.8	3.7	2.7	1.9	3.0	2.3	2.0	–
Max	−8	−6	8.9	−12	13	17.7	−9	−6	9.0	6.00
					2000					
Mean	0.4	1.0	3.6	0.1	2.0	4.0	1.4	1.3	7.4	2.42
RMS	3.3	2.3	2.1	3.8	2.0	2.5	7.6	2.2	3.4	–
Max	14	−7	14.6	21	−6	21.1	14	−5	14.3	7.05

Notes:
1) *y* is displacement (in pixels) along the axis oriented from the south to the north along the satellite trajectory;
2) *x* is displacement (in pixels) along the axis oriented from the west to the east along the scanning direction;
3) *D* is error (km) in calculation of objects' coordinates in the image;
4) TLE is the age of TLE files (days);
5) RMS is the RMS deviation;
6) Max is the maximum value of a characteristic.

For different types of satellites, the number of such images is in the percentage 50:25:25, respectively, for NOAA–12, –14 and –15. Most glint situations (more than 70%) fall on the most informative afternoon images. In the literature, there are almost no algorithms allowing reliable automatic separation of subpixel sun glints and fires for areas with a large number of rivers and water bodies like the Tomsk Region.

To solve this problem, a combined algorithm for rejection of sun glints has been developed. This algorithm, which has been in use since 1999, includes: (a) spatial statistical analysis of satellite measurements; (b) analysis of values measured in all the AVHRR channels with allowance for the observation geometry; and (c) the use of hydrographic data of the Tomsk Region. Application of this algorithm has shown high efficiency, characterized by a level of sun glint rejection higher than 95%.

For early detection of forest fires, of particular importance is the problem of accuracy of the determination of an object's coordinates, which determines the efficiency of fire fighting measures undertaken by fire management agencies. As it was already mentioned, georeferencing is performed by the commonly known

SGP4 algorithms based on the files with orbital data like TLE-NORAD Two-Line Elements Set (TLE-file), which are updated by the operator five times a week through the Internet from (http://celestrak.com/NORAD/elements/noaa.txt). The accuracy of this method was analyzed for 1840 images, and the results of this analysis are given in Table VI.

Table VI shows that additional corrections to this georeferencing are needed. The calculated location of an object differs from reality by 3.5–4.5 km, on the average, reaching 10–20 km in some cases, and this cannot be accepted as a satisfactory accuracy. An analysis was conducted to examine the dependence of accuracy of geographic reference on the age of the TLE-file, i.e., the difference between the time of reception of satellite images and the time of observation given in the first line of a file with orbital data. The results of the analysis demonstrated that such dependence (within 6 days) is almost absent and even for the TLE-file less than 1 day old the error in calculation of the geographic reference may exceed 10 km. Thus, the error cannot be minimized by using only "fresh" orbital data. This conclusion is well illustrated by the data of Table VI for 1998, which were obtained based on the archive of TLE-files from (http://celestrak.com/NORAD/archives/), where their age was within 10 hours.

To solve this problem a program of interactive linear correction of the calculated geographic reference was developed. This program uses a set of reference points and contour hydrographic lines. Its efficiency was estimated based on an analysis of 1840 space images. The results of this analysis showed that geographic reference can be efficiently corrected in more than 95% of the situations, while failures, representing only a low percentage of cases, occur in the presence of large (about 80–100%) fractional cloud cover of the image. It should be also noted that for 75–80% of images the algorithms automatically calculate correction parameters.

One of the most obvious ways to increase the efficiency of automatic detection of high-temperature anomalies, whose size is one to two orders of magnitude smaller than the AVHRR spatial resolution, involves atmospheric correction of satellite data based on coincident optical conditions and observational geometry. Analysis of literature data indicates that, since this problem is very complicated, most algorithms for satellite detection of forest fires in practice usually omit atmospheric correction. At the same time, even under the conditions of the transparent atmosphere, the atmospheric extinction coefficient for the upward thermal radiation emitted by a fire is about 0.8–0.5 for the AVHRR scan angles ($\Theta = 0$–55°). As the aerosol concentration increases, this coefficient additionally decreases (1.5–2 times) with the increase of the aerosol optical depth.

Development of efficient procedures for early detection of subpixel fires requires consideration of such an interfering factor as the solar radiation reflected by the surface and scattered by the atmosphere (solar haze) in AVHRR channel 3 (3.75 μm). To do this, a fixed threshold value (ignoring even the position of the sun) or a parameter depending actually only on the solar zenith angle is usually selected.

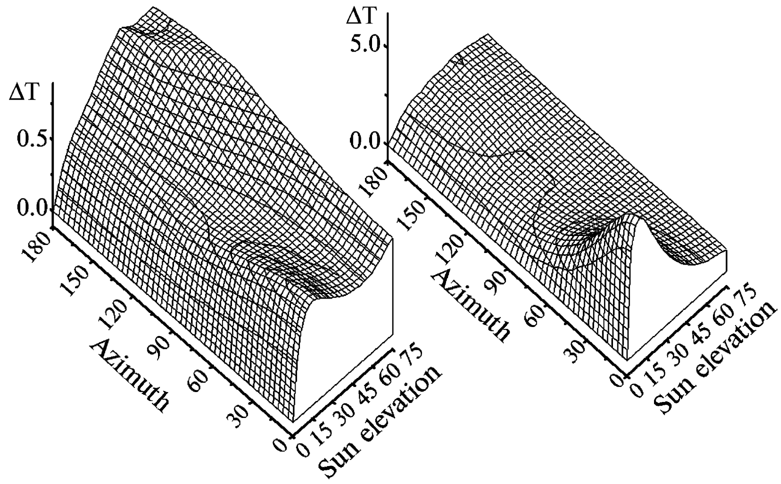

Figure 8. Contribution (δT, Kelvins) of solar haze to AVHRR channel 3 brightness temperature. The plots correspond to rural aerosol model, visibility 5 km (observation angle Q is 20 on the left side of figure and Q is 40 on the right side).

Figure 8 illustrates the complicated dependence of the solar contribution to the brightness temperature in AVHRR channel 3 on the optical and geometrical observation conditions. It depicts the results of numerical simulation of this parameter for different observation angles (Θ), zenith (altitude) and azimuth angles of the sun and a wide range of optical thickness of the near-surface aerosol. As can be seen, with the solar elevation ranging within 5–15°, a peak of the solar haze is formed. The amplitude of this peak depends on the optical characteristics of the near-surface aerosol and the viewing zenith angle. This case is characterized by the significant dependence of the brightness temperature on solar haze and on the relative azimuth angle. Algorithms taking into account the main interfering atmospheric factors in the problem of space monitoring of subpixel thermal anomalies are now under development.

Conclusion and Future Plans

In Russia there exists a multilevel spatially distributed system for space monitoring of forest fires based on NOAA AVHRR and TOVS data. The federal-level system has been reliably and stably operating since 1999. The results of the thematic processing of AVHRR images are useful for almost any team within the forest fire management agencies and other forestry departments. The capabilities of this system allow not only the prompt use of the satellite information for making management decisions on the organization of fire fighting measures, but also for assessment of potential fire consequences. Regional centers for the reception and processing of satellite data complement the regional-level systems, increasing their reliability and efficiency. These centers deal with development and testing of new, advanced algorithms for thematic processing of satellite data taking into account regional specifics and the possibility of the quick validation of algorithmic solutions for a wide range of problems related to the prediction, early detection, and assessment of consequences of forest fires in Siberia.

The immediate tasks as planned by the authors of this paper are the determination of criteria and procedures for the evaluation of the efficiency of algorithms for thematic processing of satellite information in the interests of Russian forestry and the development of advanced prognostic models of appearance and development of forest fires. Early detection of forest fires from space still remains an object of our attention. The solution of these problems assumes the use (and comparison) of the capabilities of other satellite systems.

Acquisition and processing of direct broadcast (DB) data from the Moderate Resolution Imaging Spectrodadiometer (MODIS) on the NASA Earth Observing System (EOS) Terra and Aqua satellites has begun recently at several institutions in Russia. This activity is being carried out in partnership with the MODIS fire team at the University of Maryland, Department of Geography, and NASA Goddard Space Flight Center (Justice et al. 2002). The MODIS fire team is providing processing software and works with the Russian partners on the regional evaluation of the MODIS fire products, which are currently integrated into the suite of fire information on an experimental basis. In addition to DB data, fire locations from the MODIS Land Rapid Response System (Justice et al. 2002) are also available and can be used as backup in case of a DB transmission or processing failure. Ultimately, the better radiometric and geometric characteristics of MODIS will enable the operational generation of more accurate fire products than those from AVHRR.

The fire monitoring activities described in this paper are being organized into a Northern Eurasian regional network of the Global Observation of Forest and Landcover Dynamics (GOFC/GOLD) program (Justice et al. 2003). This program, among other objectives, promotes free data sharing and the comprehensive evaluation of data products. Validation is done using high-resolution imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on Terra (Yamaguchi et al. 1998) and the Enhanced Thematic Mapper (ETM+) on Landsat-7.

Preparations are also underway for the processing of data from the next generation of operational environmental satellites from NPOESS (National Polar-Orbiting Environmental Satellite System) and NPP (NPOESS Preparatory Project). MODIS is being used as a proxy for the Visible/Infrared/Imager/Radiometer Suite (VIIRS), which will replace the current AVHRR sensor on these missions (Townshend and Justice 2002).

While real-time fire products are primarily generated to facilitate prompt decision making within the various fire management agencies, fire products are also essential for the Russian and international science community for the analysis of the local, regional and global effects of biomass burning in Northern Eurasia. The emerging GOFC/GOLD regional network described in this paper has been recognized as a major data provider for international research programs such as the new Northern Eurasian Earth Science Partnership Initiative (NEESPI).

Acknowledgements

I. Csiszar's and T. Loboda's participation in fire product development and validation activities in Russia has been supported by the NASA New Investigator in Earth Science and the NASA Land Cover Land Use Change programs.

References

Abushenko, N.A., Altyntsev, D.A., Min'ko, N.P., Semenov, S.M., Tashchilin, S.A. and Tatarnikov, A.V.: 1999a, 'Algorithm for fire detection based on multispectral AVHRR data', Abstracts of Papers at VI Intern. Symp. on Atmospheric and Ocean Optics, Tomsk: Spektr, p. 69.

Abushenko, N.A., Bartalev, S.A., Belyaev, A.I., Ershov, V.V., Korovin, G.N., Koshelev, V.V., Loupian, E.A., Krasheninnikova, Yu.S., Mazurov, A.A., Min'ko, N.P., Nazirov, R.R., Proshin, A.A. and Flitman, E.V.: 2000, 'System for acquisition, processing, and distribution of satellite data for on-line solution of problems of the Russian Forest Fire Control Service', Naukoemkie Tekhnologii. Vol. 1. No. 2, pp. 4–18. (in Russian)

Abushenko, N.A., Bartalev, S.A., Belyaev, A.I., Ershov, D.V., Zakharov, M.Yu., Loupian, E.A., Korovin, G.N., Koshelev, V.V., Krasheninnikova, Yu.S., Mazurov, A.A., Min'ko, N.P., Nazirov, R.R., Semenov, S.M., Tashchilin, S.A., Flitman, E.V. and Shchetinskii, V.E.: 1998a, 'Experience and promises of organization of prompt satellite monitoring of the Russian territory for forest fire control', Issled. Zemli iz Kosmosa. No. 3. 89–95. (in Russian)

Abushenko, N.A., Min'ko, N.P., Semenov, S.M., Tashchilin, S.A. and Tatarnikov, A.V.: 1999b, 'Automatic algorithm for forest fire detection from multispectral NOAA AVHRR data', Proc. of III Russian Scientific Conf. "Application of Remote Radiophysical Methods in Environmental Research", -Murom, pp. 210–211. (in Russian)

Abushenko, N.A., Min'ko, N.P., Semenov, S.M., Tashchilin, S.A. and Tatarnikov, A.V.: 1998b, 'Development of the automatic algorithm for fire detection based on NOAA AVHRR data for the territory of Eastern Siberia', Proc. of Intern. School of Young Scientist and Specialists "Environmental Physics", Tomsk.

Abushenko, N.A., Tatarnikov, A.V., Tashchilin, S.A., Vladimirov, I.N. and Cherkashin, A.K.: 2002, 'Development of integrated multilevel GIS for monitoring of forest fires and prediction of dynamics of forest resources', Abstracts of Reports at Siberian Regional GIS Conference. – Moscow: GIS-Association, pp. 35–38. (in Russian)

Afonin, S.V. and Belov, V.V.: 2002, 'Efficiency of satellite technologies as applied to prompt monitoring of forest fires in the Tomsk Region', Issled. Zemli iz Kosmosa. 1, 42–50. (in Russian)

Afonin, S.V., Belov, V.V. and Gridnev, Yu.V.: 2000, 'System of the space-based monitoring of forest fires on the territory of Tomsk Region', Atmos. Oceanic Opt., Vol. 13. No. 11, 921–929.

Arino, O., Melinotte, J.M., Rosaz, J.M. and Monjoux, E.: 1997, 'ESA Fire Product', *Proceedings of the 7th ISPRS Conference on Physical Measurement and Signatures in Remote Sensing*, Courchevel, pp. 7–11.

Bartalev, S.A., Loupian, E.A., Shchetinskii, V.E. et al.: 1998a, 'Experience and promises of organization of prompt satellite monitoring of the Russian territory for forest fire control', Issled. Zemli iz Kosmosa. No. 3, 89–95. (in Russian)

Belyaev, A.I., Korovin, G.N., Loupian, E.A. et al.: 1998, 'Development of GIS for monitoring of forest fires in Russia based on ARCVIEW GIS 3.0 and the Internet', ARCREVIEW – modern GIS technologies. No. 1 (4), pp. 6–7.

Boles, S.H. and Verbyla, D.L.: 2000, 'Comparison of three AVHRR-based fire detection algorithms for interior Alaska', *Remote Sensing of Environment*, **72**, 1–16.

Bukchin, M.A., Gershenzon, V.E., Zakharov, M.Yu. et al.: 1992, 'Possibilities of creation and promises of the use of cheap stations for reception of data from NOAA satellites in the HRPT mode', Issled. Zemli iz Kosmosa. 1992. No. 6, 85–90. (in Russian)

Bukchin, M.A., Loupian, E.A., Mazurov, A.A. et al.: 1994, 'Primary processing of data of meteorological satellites at local receiving stations', Issled. Zemli iz Kosmosa. No. 5, 112–117. (in Russian)

Flasse, S.P. and Ceccato, P.S.: 1996, 'A contextual algorithm for AVHRR fire detection', Int. J. Rem. Sens., Vol. 17, No. 2, pp. 419–424.

Hoots, F.R. and Roehrich, R.L.: 1988,'Models for Propagation of NORAD Element Set (Package Compiled by T.S. Kelso): Spacetrack Report, 3', Defense Documentation Center. Alexandria, p. 49.

Justice, C.O., Giglio, L., Korontzi, S., Owens, J., Morisette, J.T., Roy, D., Descloitres, J., Alleaume, S., Petitcolin, F. and Kaufman, Y.J. 2002: 'The MODIS fire products', *Remote Sensing of Environment*, **83**, 244–262.

Justice, C.O., Smith, R., Gill, M. and Csiszar, I.: 2003, 'A review of current space-based fire monitoring in Australia and the GOFC/GOLD program for international coordination', *International Journal of Wildland Fire* **12**, 247–258.

Kaufman, Y.J. and Justice, C.: 1998, 'MODIS ATBD': Fire Products (Version 2.2 Nov. 10 1998). EOS ID#2741, p. 77.

Kaufman, Y.J., Tucker, C.J. and Fung, I.: 1990, 'Remote sensing of biomass burning in the tropic', J. Geophys. Res. **95**, 9927–9939.

Kondranin, T.V. and Ovchinnikova, E.V.: 1995, 'Simulation of the efficiency of algorithms for recognition of a thermal anomaly like forest fire from space', Issled. Zemli iz Kosmosa. No. 6, 51–57. (in Russian)

KOSDAN: Space system for acquisition of earth data. 1992 System project. Moscow, Russian Space Agency. (in Russian)

Korovin, G.N. and Andreev, N.A.: 1988, 'Air Fire Protection', Moscow: Agropromizdat. 220 pp. (in Russian)

Li, Z. and Giglio, L.: 1999, 'A Review of AVHRR-based Fire Detection Algorithm – Forest Fire Monitoring and Mapping: A Component of Global Observation of Forest Cover', Report of Workshop. Joint Research Centre, Ispra, Italy. November 3–5, p. 256.

Loupian, E.A., Mazurov, A.A., Nazirov, R.R., Proshin, A.A. and Flitman, E.V.: 1999, 'Development of Databases for the Systems for Acquisition, Processing and Distribution of Satellite Data CSIT'99', *Proceedings of 1st International Workshop on Computer Science and Information Technologies, January 18–22*, Moscow, Russia. MEPhI Publishing 1999, ISBN 5-7262-0263-5.

Loupian, E.A., Mazurov, A.A., Proshin, A.A. et al.: 1998, 'System for automatic reception and archiving of satellite data', Preprint of SRI RAS. Pr-1988. Moscow, pp. 19. (in Russian)

Loupian, E.A., Zakharov, M.Yu., Mazurov, A.A. and Flitman, E.V.: 1995, 'Flexible System of Updating Software for Satellite Images Processing', *Proc. 1st International Symposium on 'Reducing the Cost of Spacecraft Ground Systems and Operations*', Chilton, Oxfordshire. pp. 61.1–61.5.

Lykov, A.V.: 1968, 'Drying Theory', Moscow, Energia. (in Russian)

Ponomarev, E.I. and Sukhinin, A.I.: 2000, 'Combined evaluation of fire hazard and prediction of energy parameters of forest fires with the use of geoinformation databases', Computer technologies. Novosibirsk, Vol. 5, 58–68. (in Russian)

Swain, P.H. and Davis, S.M. (eds.), 'Remote Sensing: The Quantitative Approach', 1978. McGraw Hill New York, p. 415.

Shchetinskii, V.E.: 1984, 'Organization of forest fire control in the USSR', UN Intern. Training Seminar on Practical Application of Remote Sensing Data in Forestry. Moscow, pp. 1–9.

Shikin, E.V., Boreskov, A.V. and Zaitsev, A.A.: 1993, 'Principles of computer graphics', Moscow, Dialog-MIFI. (in Russian)

Sukhinin, A.I.: 1996, 'System for space monitoring of forest fires in Krasnoyarskii Krai', Sib. Ekol. Zh. Vol. 3. No. 1, pp. 85–91. (in Russian)

Sukhinin, A.I., Cahoon, D.R. and Stocks, B.J.: 1999a, 'Remote sensing of forest fires in Siberia using NOAA information', Int. Conf. 'Forest Fires: Appearance, Extinguishing and Ecological Consequences', Abstracts of Papers. Tomsk: Tomsk State University Publishing House, pp. 123–125.

Sukhinin, A.I., Kashkin, V.B. and Ponomarev, E.I.: 1999b, 'Monitoring forest fire in Eastern Siberia from space', Sixth International Symposium on Atmospheric and Ocean Optics, Proceedings of SPIE, Vol. 3983, pp. 206–214.

Townshend, J.R.G. and Justice, C.O.: 2002, 'Towards operational monitoring of terrestrial systems by moderate-resolution remote sensing', *Remote Sensing of Environment* **83**, 351–359.

Valendik, E.N., Dorrer, G.A. and Sukhinin, A.I.: 1983, 'System for remote control and prompt prediction of forest fire propagation', Collection of papers. Space Methods of Studying the Environment in Siberia and Far East, Novosibirsk, Nauka, pp.136–155. (in Russian)

Vonskii, S.M., Zhdanko, V.A., Korbut, V.I., Semenov, M.M., Tetyusheva, L.V. and Zavgorodnyaya, L.S.: 1975, 'Drawing and application of local scales of fire hazard in the forest', Leningrad: LenNIILKh, pp. 57. (in Russian)

Yamaguchi, Y., Kahle, A.B., Tsu, H., Kawakami, T. and Pniel, M.: 1998, 'Overview of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)', *IEEE Transactions on Geoscience and Remote Sensing* **46**, 1062–1071.

Zakharov, M.Yu. and Loupian, E.A.: 1993, 'Organization of record format for data from NOAA satellites for solution of local problems', Issled. Zemli iz Kosmosa. No. 3, pp. 66–70. (in Russian)

Zakharov, M.Yu., Loupian, E.A., Mazurov, A.A., Nazirov, R.R. and Flitman, E.V.: 1997, 'Development of fully automated systems for satellite data acquisition with remote control over the internet', 2nd International Symposium on "Reducing the Cost of Spacecraft Ground Systems and Operations". RAL Keble College. Oxford p. 76.1–76.10.

Zhdanko, V.A. and Gritsenko, M.V.: 1980, 'Method for analysis of forest fire seasons', Practical recommendations. LNIILKh. Leningrad. (in Russian)

Zherebtsov, G.A., Kokurov, V.D., Koshelev, V.V. and Min'ko, N.P.:1995, 'The use of NOAA AVHRR data for forest fire detection', Issled. Zemli iz Kosmosa. No. 5, 74–77. (in Russian)