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An Overview of Remote Sensing in Russian Forestry

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Abstract

The Russian Federation possesses vast forested areas, containing about 23% of the world's closed forests. A significant part of these forestlands is neither managed nor regularly monitored. This is due in part to the absence of developed infrastructure in the remote northern regions, which hampers the collection of data on forest inventory and monitoring in all areas by precise and expensive on-ground methods. As a result, the former Soviet Union conducted intensive research on remote sensing during the last few decades, resulting in significant achievements. However, there has been a noticeable decline in remote sensing research and applications in the Russian forest sector from 1990–1998.

Russia needs a new system of forest inventory and monitoring capable of providing reliable, practical information for sustainable forest management. Such a system should take into account current national demands on the Russian forest sector as well as the international obligations of the country. Remote sensing methods are an indispensable part of such a system. These methods will play a crucial role in critical applications such as ensuring the sustainability of forest management, protecting threatened forests, fulfilling the country's Kyoto Protocol obligations, and others.

This paper presents an overview of past and current remote sensing methods in the Russian forest sector, including both practical and scientific applications. Based on this overview, relevant applications of remote sensing methods in the Russian forest sector are discussed. This discussion considers current Russian economic conditions and the direction of political and social development of the country.

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An Overview of Remote Sensing in Russian Forestry

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1 Introduction

An extensive scientific program to study forest ecosystems using remote sensing was initiated in the USSR in the beginning of 1970s. This program included the development of methods of remote sensing for forestry, forest management, and environmental protection. The basic research was mainly concentrated in the Forest and Wood Institute in Krasnoyarsk, part of the Siberian Branch of the Russian Academy of Sciences (SBRAS). This institute is currently known as the SBRAS Forest Institute. Applied research was conducted at the Scientific and Research Department of the All-Union Association of Forest Inventory and Planning Enterprises (*Vsesojusnoe Lesoustroitel'noe Ob'edinenije "Lesproekt"*), currently a part of the All-Russia Research and Information Center on Forest Resources (*VNIIZ Lesresurs*). This institution was established in 1972 and is focused on the development and implementation of remote sensing methods in forestry. At that time, the Leningrad (currently St. Petersburg) Forestry Research Institute obtained the first experimental results on forest fire detection using space-based systems.

A series of monographs (Investigations of Taiga Landscapes…, 1979; Remote Identification of Taiga…, 1981; Remote Investigations of Landscapes, 1987) were published in the 1980s. These monographs summarized basic research on the formation of forest landscapes, mapping of their spatial structure, and division of forest territories into homogeneous regions (a process known as *regionalization*). The improvement of satellite systems during the 1980s and the growing interest in implementation of remote sensing in different branches of economy and science resulted in numerous publications on the topic of remote sensing. The monograph series demonstrated the growth of scientific experience in forest ecosystem observation and the importance of these results for practical applications. The first manuals, practical demonstrations of remote sensing methods in forest inventory and mapping, and methods for remote sensing accounting of contemporary changes in forests of the taiga regions were issued during the 1980s.

The major goals of this report are as follows:

- to summarize the accumulated experience in implementing remote sensing methods in basic and applied forest ecosystem research in the USSR and Russia which has been gained over the last few decades;
- to describe the methods and results of implementation of aerial and space-based data collection systems in forestry and forest management; and,
- based on the above analyses, and taking into account the international development of remote sensing applications, to evaluate urgent research needs in the field and to propose a relevant structure for a remote sensing component of the proposed Russian New Forest Inventory and Monitoring System (NFIMS).

In this overview of remote sensing methods used in Russian forestry, the main focus is on remotely sensed information gathered by Soviet and Russian space-based systems. Russian scientists are also currently using images from Western space-based systems in combination with images from domestic systems, usually within the framework of international projects and programs. A brief description of these programs is also presented in this overview.

Issues concerning remote sensing devices, the extent of information in available sources, and methods of their implementation are described according to their usefulness for forestry and investigations of forest ecosystems. Emphasis is placed on space-based systems where data are fully accessible and widely used by different customers. Aspects of the practical use of military space-based systems and observations from orbital space stations are also briefly described. Future space programs, currently in an experimental status, are briefly characterized.

2 Historical Background

Implementation of aircraft based photographic methods in Russian forestry began in the 1920s. During the recovery period of the Soviet economy after the Civil War, it became necessary to find newer and more efficient methods to assess and inventory the forests in order to meet demands for wood. The use of aircraft for this task was first discussed at the Forest Conference in 1921. A widely recognized Russian forest scientist, G.M. Turskii, presented proposals on ways in which aerial photographs could be used for forest inventory purposes. The first usable aerial photographs for the purpose of forest inventory assessment were made over the territories of the Leningrad and Kalinin (currently Tverskaya) regions in 1925. These photographs were made at the scale of 1:8400 and demonstrated the potential of aerial photography in forest inventory assessment (Dmitriev *et al.*, 1989).

Significant results using aerial photography, in both experimental research and practical implementation in forest management and forest inventory, were obtained before the Second World War (1926–1940). Among the most important results were:

- the development of methods for vegetation interpretation;
- the establishment of a combined inventory method, involving the combination of ground based measurements with interpretation of aerial photographs; and
- the estimation of the accuracy of aerial photographic methods in forest inventory assessment.

During this period A.E. Novoselyskii, A.K. Pronin, and G.G. Samoilovich made valuable contributions to the development of forest inventory methods using aerial photography.

After the Second World War, investigations were continued and intensified. Basic research was concentrated at the Forest-Technical Academy (*Lesotekhnicheskaja Akademija*) in Leningrad. The All-Union Association (AUA) "*Lesproect*" was established in 1947 specifically for the practical implementation of new methods in forest inventory assessment. Scientists from "*Lesproect*" and from the Forest-Technical Academy initiated numerous experimental projects on forest interpretation based on black-and-white aerial photographs (primarily in the scale of 1:15000) combined with a limited on-ground measurement of forest stands in 1949–1951.

Large-scale experiments using spectrazonal aerial photography were conducted in the 1950s. These experiments examined the use of spectrazonal aerial photography for the conduct of forest inventories, the monitoring of forest conditions, and the efficiency of forest operations. These investigations were initiated by the Air Methods Laboratory of the Academy of Sciences of the USSR (located in Leningrad) and were further developed by a number of other institutions, including the Scientific and Industrial groups of the Forest Technical Academy, the AUA "*Lesproect*", the Leningrad Forestry Research Institute, and the SBRAS Forest and Wood Institute.

At the same time, G.G. Samoilovich made significant contributions to the theory of interpretation of aerial photographs with respect to indicators of forest stands, homogeneous forested areas, and different categories of forest lands. He also developed methods for investigating the structure of forests by interpretation of aerial photographs, proposed a system for the classification of the crown shapes of trees, determined dependencies between image characteristics and biometric indicators of stands, proposed a system for forest inventory based on instrumental interpretation of aerial photographic images, and developed a method known as *air taxation* (a method of visual description of forests from aircrafts) (Samoilovich, 1964).

At this time, topographic and geodesic enterprises resulted in the completion of a topographic survey and 1:100000 scale map of the territory of the USSR based on aerial photographs (Knizhnikov, 1997).

In the 1960s, the Forest-Technical Academy, AUA "*Lesproect*", and the Leningrad Forestry Research Institute developed new technologies for forest inventory assessment. These were based on a combination of interpretation of spectrazonal images using laboratory instruments together with combined ground-based visual and measured assessments. This technology is still in use. The Regional Forest Inventory Enterprises of the AUA *“Lesproect”* also used spectrazonal aerial photographs in the assessment of forest inventories for large areas (Gusev, 1998).

The first observations of forests from satellites were made in 1960. Observations by astronaut G.S. Titov from a piloted spacecraft followed in 1961. These two space flights symbolized the beginning of space-based methods in natural resources observation and the development of applications of space-based methods for observation and investigation of forests.

During the 1970s and 1980s, scientists from AUA “*Lesproect*” developed and implemented methods for:

- carrying out inventories of remote unused territories in the Russian forest reserve area;
- thematic mapping; and
- estimation of the condition of forests damaged by fires, insects, natural calamities, etc.

These methods relied on space-based observation combined with aerial photography. The first experiments on automatic interpretation of space-based and aerial images dates from the same period. Algorithms and methods for automatic processing of remotely sensed information were developed as a result of intensive research. These results were developed into special technologies and were implemented in experimental systems for automatic processing of forest information collected from aerial and space-based platforms.

Interpretation of aerospace images of landscapes was begun by the Air Methods Laboratory of the Academy of Sciences of the USSR in St. Petersburg and was further developed by the SBRAS Forest and Wood Institute in Krasnoyarsk and Novosibirsk. Investigation of forest and desert shrub vegetation was carried out mainly at the Deserts Institute of the Academy of Sciences of Turkmenskaya SSR in Ashabad (Dmitriev *et al.*, 1989).

Scientists from the Leningrad Forestry Research Institute initiated applied research on protection against forest fires using spaceborne equipment. Their applied methodology for forest fire protection is now in regular use (Implementation of Satellite Information …, 1977).

Such well recognized scientists as V.I. Sukhihk, A.S. Isaev, E.P. Danjulis, V.M. Zhirin, D.M. Kireev, I.A. Krenev, V.I. Berezin, V.N. Sedykh, E.N. Valendik, V.V. Furyaev, N.G. Kharin, R.I. Elman and their scholars and followers made significant contributions to the development of basic and applied methods of forest studies using remotely sensed data (Gusev and Sinitsyn, 1981; Isaev, 1995; Gusev, 1998).

Appendix 1 contains a list of the most important official documents which regulate the application of remote sensing methods in forestry. Appendix 2 lists a number of the basic methodological documents (manuals, instructions, reference and normative data) which, after experimental work and field testing, have been recommended for use in the forest sector.

During the last decade, a number of advanced technologies have been developed for satellite remote sensing methods. Current developments in remote sensing applications includes the development of new computer tools for automatic treatment and interpretation of satellite images, as well as the increased use of geographic information systems. However, a decline in the applied use of remote sensing methods has been observed over the last decade (Isaev and Sukhikh, 1998). Efforts have concentrated on scientific and ecological problems, such as the assessment of the productivity of terrestrial biota of large regions and the evaluation of biospheric functions of forests in terms of biodiversity and the global carbon cycle. These are the primary problems examined in ongoing international projects.

One of the most important current tasks in the development of remote sensing methods deals with the organization and implementation of forest monitoring (Isaev and Sukhikh, 1979; Isaev, 1995). The main issues are:

- aggregating available remotely sensed data and developing methods for image processing;
- combination of different tools and sensors for airborne and space-based observation with visual aerial observation and partial video surveys;
- combination of remotely sensed information flows with digital mapping, forest inventory in GIS-environment; and
- accurate and reliable geo-referencing of remotely sensed data using portable global positioning system (GPS) receivers.

3 Tools for Remote Sensing of Forests

Remote sensing techniques provide information, from aircraft-based and space-based sensors, for basic and applied research into forest ecosystems. These techniques include photographic, scanner, video, radar, IR-thermal, radiometric, and multispectral systems. In some projects, this information is combined with visual observations from space, airplanes and selected ground-truth data. Nevertheless, spectrazonal photo images from relatively old but well-known satellites such as the “Kosmos” series and from new generations of the “Resource-F” series are widely used for applied forestry tasks. Spectrazonal space photos have a high spatial resolution (5 to 10 meters) and, in spite of some predictions in the 1970s and the 1980s that they would be replaced by multispectral photo and scanner images, they are still the main sources of remote sensing information in forest surveys and investigations.

At present, due to the economic decline and the financial problems in Russia, the costs of remotely sensed information are a significant problem. During the 1970s and 1980s, all Russian institutions and scientific groups had full access to free remotely sensed data. From the beginning of 1990s, users must pay for preliminary orders (planning and acquisition of images for selected regions) and image production. The cost of one spectrazonal photo image (according to the official price list at the beginning of 1998) was approximately US$ 85–100, and the cost of the information in digital form (in a raster format specified by the user) was in the range of US$ 680–1000. This is not as expensive as images from western satellites, but for many Russian scientific groups and institutions it is not affordable. This, as well as the absence of guarantees that the ordered images will be delivered, is likely to support more penetration of scanner digital images in the market at the expense of photographic images. In addition, such a replacement of paper technologies with digital computer technologies is likely to stimulate the more general transition to computer-based automatic image processing. These automatic techniques are currently constrained by high prices of the techniques and software.

According to a recent decision by the Russian Space Agency, information from the medium resolution scanner MSU-SK (installed on the "Resource-01" satellite) is free and does not require any preliminary request. Therefore, Russian users today have free operational access to digital satellite data. Also, Russian customers can order high-resolution MSU-E scanner images on favorable terms. The price is about US$ 80, which is ten times less expensive than analog data from western satellites such as LANDSAT and SPOT (Garbuck and Gershenzon, 1997).

The results of a questionnaire sent to representatives of different institutions are presented below (Efimov and Miller, 1997). The institutions selected for the questionnaire were those which determine state policy for Russian space programs, as well as other consumers of space-based information. The main impediments to the development of a Russian market in remotely sensed data are:

1. Access to information on the availability, parameters, and quality of remotely sensed data for specific territories is difficult.
2. There is no guarantee that images of a specific region ordered from Russian data producers will be obtained.
3. The quality of the Russian remotely sensed data as a commercial product (e.g., standardization of formats supplying meta-data, complete characterization of remote sensing conditions and techniques) is low.
4. Information on the availability of digital thematic and topographic products, which is important for implementation of remotely sensed data, is unavailable.
5. Remote sensing conducted by Russian space-based platforms and the production of new satellite sensors does not reflect user requirements.

6. Potential users have insufficient knowledge of relevant applications of remote sensing methods.
7. The security requirements for using remotely sensed data and maps is unnecessarily strict.
8. Domestic remotely sensed data is expensive.

It is evident from the questionnaire that the security regime was not indicated as the main problem for the development of remote sensing methodologies. Nevertheless, some of the restrictive features of the previous security regime have been restored during the last two years. Providing consumers with current archive data at acceptable prices will be a major prerequisite for increased use of remotely sensed data. The current monopoly holder on some of the remote information, and the combination of high prices and lack of fulfillment of orders by this monopoly, are major impediments for development.

Space-based photographic remote sensing systems were developed more intensively and more successfully in the USSR, and later in Russia, than abroad (Streltsov and Gorelov, 1990; Sukhikh, 1995, 1996). An advanced infrastructure for photographic image processing was developed in Russia. This, as well as the advantages of using photographic images, stimulated the wide implementation, perfection, and pre-eminence of these space-based systems during the 1980s.

Space images of territories for different civil departments are conducted in Russia by a technique established with satellites of the "Resource-F" series (which have been regularly updated since 1975). *Table 1* shows the main characteristics of photographic images from the "Resource-F" series satellites (Korolev and Baranov, 1996b).

Table 1: Characteristics of photo images from "Resource-F" satellite series (Korolev and Baranov, 1996b).

Characteristics	**3.1.1 Photo Camera**			
	MK-4	**KATE-200**	**KFA-1000**	**KFA-3000**
Average scale of image	1:1000000	1:1300000	1:270000	1:100000
Size of the negative, cm	18×18	18×18	30×30	30×30
Spatial resolution, m	8–10	20	5–10	2–3
Longitudinal overlap, %	60	60	60	30
Spectral channels (μm) and types of film	0.515–0.565 0.58–0.80 0.635–0.69 0.81–0.90	0.48–0.60 0.60–0.70 0.70–0.85	2-layer spectral film 0.57–0.81	black-and-white panchromatic film
Field of view, sq. km.	30–000	50–000	6400	440

For forest inventory and mapping, the observation of the dynamics of reforestation, and other long term processes, the data interval may be between 5 and 10 years. In this case, the timing of information reception is not that important, and preference is given to detailed space photo images with high spatial resolution in optical and near IR-channels. Images taken by photographic cameras orbiting the Earth are available in special capsules after the end of the flight. This results in a low operational speed for receiving these photographic images from space. These images must then be scanned and converted to digital form for computer assessment. Nevertheless, until recently, only photographic images were able to satisfy customer demands for high image quality (e.g., the high spatial resolution, high geometrical accuracy and the availability of overlapping photos necessary for stereoscopic analysis).

The state center “Priroda” is the only distributor of space images from the “Resource-F” satellites. Previously, satellites of this series were launched 2–3 times per year specifically to provide information to civil branches of government of the USSR. Between 1993 and 1996 there were no satellite launches of this series, due to the low customer demand caused by the lack of guarantees on delivery of images for specified areas.

There is presently the opportunity to use the high resolution space photo images taken by Russian national security space-based systems. These images are useful for civil agencies and for international projects. Black-and-white panchromatic images taken by TK-350 and KBR-1000 cameras are also considered as valuable sources of information for forestry purposes.

The focal distance (f=350mm) of the TK-350 camera lens allows particularly precise geometric characterization of images. Images have a 10 m spatial resolution and an average scale of 1:660000. Each image covers 200×300 km with an overlap of 80% and 60%, which allows the use of these images in conducting stereo model measurements.

The KBR-1000 (f=1000 mm) camera is a high resolution panoramic camera with a different geometry than the TK-350, and is equipped with a lens that can move during exposure. This results in a long belt (which covers a 40×180 km area) on the negative. The main characteristics of space images taken by this camera include a spatial resolution of 2 m, an average scale of 1:220000, a negative size of 18×18 cm, an area covered by one image of 40×40 km, and no longitudinal overlap. Due to high spatial resolution and geometric accuracy, images from the TK-350 can be enlarged to the scale of 1:50000, and images from the KBR-1000 to the scale of 1:10000, without a noticeable reduction in quality. The combined use of declassified images from KBR-1000 and TK-350 cameras and from spaceborne equipment makes it possible to obtain topographic maps at a scale of 1:50000, as well as GIS products. The exclusive rights for Russian distribution of the declassified high resolution space images belong to the International Association *“Sovinformsputnic”* (Lavrov, 1997).

Space images from US national security systems have analagous characteristics. Over the years, images were taken with panchromatic black-and-white films by the KH-1, -2, -3, -4, -4A, -4B, -5, and -6 series photographic cameras with resolutions from 12–8 m (KH-1 through KH-3) to 1.8 m (KH-6). The first images taken by KH-1 through KH-3 had no overlap. Subsequent images had sufficient coverage to make stereoscopic pairs. Later generation cameras have a panoramic scheme similar to the Russian KBR-1000. The average scale of negatives from the KH-4, KH-4A, and KH-4B cameras is about 1:300000, and the scale of negatives from the KH-6 camera is about 1:100000. The scale of images can be increased to 1:7500 to 1:12000 (Korolev and Baranov, 1996a). Declassified images archived in the defense departments of the USA and Russia are currently available to both Russian and American customers, resulting in an increased supply of available space images.

For forest ecosystem monitoring, and for the observation of short-term processes and phenomena in Russian forestry, it is necessary to obtain and process remote sensing information in close to real time. In this case, data from the technique of operational space observation are of high importance. Information is transferred from the spacecraft by radio channels, received by ground antennas, undergoes preliminary processing, and is provided to the customer in digital form and in near-real time. Scanner images have a lower resolution than photographic images, but they are more available and are thus of primary importance for the monitoring of forest fires, the detection and evaluation of thunderstorm zones, and the estimation of phenological condition of forests (by calculating the vegetation index).

The Natural Resources Survey Program, using operational meteorological and resource satellites, started in 1974 with the launching of "Meteor"-class satellites. This program was named "Meteor-Priroda" by the mass-media (Trifonov, 1981a). The implementation of the new technical equipment was done by testing the high resolution (80 m) multispectral scanner "Fragment" and "BIK-E" (borne informational complex), installed on the "Meteor-Priroda" satellite launched in 1980. In order to extend this development, the equipment for the "Resource-0" space system was created (Trifonov, 1981b). The main difference of satellites of the "Resource" type from previous satellites was the possibility of transferring images in digital form. It allows customers to use not only multispectral but also digital pictures on magnetic tapes (Garbuck and Gershenzon, 1997).

Scanner images from the satellites of the "Resource-01" series are suitable for applied research and for practical implementation in forestry. As of 1988, "Resource-01" satellites have an active life of about 3–5 years and can take images from orbits of different height. The third "Resource-01" satellite (launched in 1994) is currently active. The fourth in the series was launched in June 1998.

Instruments on "Resource-01" series satellites include the MSU-SK scanner, which is a conical scanning optical and mechanical multispectral medium resolution scanner, and the MSU-E scanner, which is a plane scanning opto-electronic multispectral high-resolution scanner.

Table 2 shows the technical characteristics of Russian space scanners on "Resource-01" satellites and the cost of the satellite information per 100 sq. km.

The transfer of real time images of MSU-SK scanner is carried out in 5 spectral bands: four in the visible and near IR bands, and one in far IR band. There is a module of two MSU-E scanners on the satellite. This allows the simultaneous observation of panoramic images (with a lower (2x) spatial resolution) taken by these two scanners in 3 spectral bands.

Table 2: Characteristics of Russian scanners and costs of the operation information (Gershenzon and Tarakanova, 1997*).*

Characteristics	**Scanner**	
	MSU-SK	**MSU-E**
Number of channels	5	3
Spectral ranges, µm	0.5–0.6 0.6–0.7 0.7–0.8 0.8–1.1 10.4–12.6	0.5–0.6 0.6–0.7 0.8–0.9
Resolution (meters in one pixel)	160 550 (in IR-thermal)	35 (along the direction of flight)
Width of the observation, km.	600	45
Periodicity of scanning of the same territory, days	4	15–20
Image cost per 100 sq. km., US$	0.36	10

Receiving, monitoring, and primary processing of operational scanner information is carried out in a national center in Obninsk (near Moscow) and in a regional center in Novosibirsk. The third center, in Khabarovsk, is not currently operating. The scanner information from "Resource-01" satellites is also received by SSC Satellitebild, a subsidiary of Swedish Space Corporation in Kiruna, Sweden. SSC Satellitebild performs geometric and radiometric correction of "Resource-01" satellite images.

The existing practice of monopolistic centralized access to scanner information, controlled by the Russian Hydrometeorologic Service, is currently changing. Small personal ground receiving stations have replaced the few large centers for data receiving and archiving. These small stations conduct receiving, registering and primary processing of remotely sensed data. Ground based equipment includes different types of antennae. These include the undirected ("Liana") antenna, the stationary directed ("Selena", "Liana-M") antennae, and antennae directed with automatic or programmed equipment

("Scan-X", "Scan-R"). The latter accompany the satellite and provides the information receiving channel in the visibility zone of ground station (Gershenzon and Tarakanova, 1997). Station installations also include software for recording the images with minimal assistance by operators.

The launching of the second generation satellites "Resource-02" (based on the "Resource-0" satellite) is planned as a part of the Russian program for natural resource investigation. These satellites will be equipped with the MSU-E1 and MSU-SK scanners and the MIVZA-M microwave sounder. The main feature of the improved MSU-E scanner is the higher (up to 25 m) spatial resolution. The MIVZA-M microwave sounder allows the determination of the total water content in the atmosphere. It operates at frequencies of 20, 35, and 94 GHz, with spatial resolutions of 80, 55, and 20 km respectively. Scanning will be carried out within the 1500 km view band (Garbuck and Gershenzon, 1997).

All-weather radar scanning is preferable for the investigation of taiga forests. Lateral vision radar systems are among the most information-rich sensors, and are typically either incoherent radar systems, with a resolution dependent on size of the real aperture of the antenna, or coherent synthetic aperture radar (SAR) systems. The high resolution of SAR is achieved by coherent processing of reflected signals received during the satellite's motion in the orbit. The advantages of incoherent radar include a wide view band and the relative simplicity of both the radar and the data processing system. However, SAR provides a much higher azimuth resolution (10–100 m) than incoherent radar (1–2 km). The resolution of modern radars is close to the resolution achievable with optical systems. Unfortunately, space-based radar systems, especially SAR, are more complicated and more expensive than other space technologies. As a result, radar-equipped space platforms are among the largest and most expensive.

Initially, SAR was used to monitor ice conditions in arctic seas. The first laterally scanning radar (working wavelength λ=3.15 cm) was installed and tested on board the "Kosmos-1500" satellite in 1983. It was a prototype of the "Ocean-01" space system. SAR was later installed on Russian satellites "Cosmos-1870", "Almaz-1" (λ=9.6 cm) and "Ocean", used for hydro-meteorological support to arctic ice-breakers (Kondratyev and Melentyev, 1995). Opportunities for wider use of radar images appeared with the launching of the operational satellite "Almaz-1A" in 1991. The SAR had the following main characteristics:

- 15 m spatial resolution,
- 30 km radar footprint,
- 350 km view band,
- linear-horizontal polarization of receiving and transferring signals,
- 15–7.5 cm working wavelength,
- 1–3 days cycle for passage over a given region.

Optical techniques were used on spacecraft for SAR signal processing and for generation of surface images. Digital information was transferred through a retranslation satellite to the Center for Data Processing and Distribution in Moscow. About 100 images were processed daily.

The distribution rights for “Almaz-1A” images were given to a special department of “Mashinostroenie”. Exclusive rights for sale of the information on the western market was first given to the Space Commerce Corporation (Houston, Texas) and then to the joint venture Almaz Corporation. The cost of one 40×40 km image on magnetic tape or floppy disk was about US $1600. An agreement on the thematic processing and distribution of radar images was later signed between “*Mashinostroenie*” and the American firm Hughes STX (Lanham, Maryland). In 1992, the cost of one 40×40 km image from the “Almaz-1A” satellite was US$ 800. In the middle of October 1992, this satellite was removed from orbit due to a lack of power (Garbuck and Gershenzon, 1997).

A continuation of the “Almaz” program and launching of new generation “Almaz-1B”, satellites is planned. Lidar, MSU-E and MSU-SK multispectral scanners, radar and other equipment are planned to be installed on this satellite. *Table 3* shows characteristics of the planned radar complex, which consists of 3 subsystems.

Table 3: Characteristics of the planned “Almaz-1B” satellite
(Garbuck and Gershenzon, 1997).

Characteristic	**SAR-3**	**SAR-10**			**SAR-70**
		Detailed mode	**Intermediate mode**	**Vision mode**	
Working wavelength, cm	3.5	9.6			70
Spatial resolution, m	5–7	5–7	15	15–40	20–40
View band, km	20–35	30–55	60–70	120–170	120–170
Field of vision, km	330	330			330
Data transfer rate, Mbit/sec	116–370	172–582	354–740	104–288	116–370

The Russian Space Agency has announced that it has given priority to the construction and launch in 1999 of the “Resource-DK” space observational complex. It will provide Russian regional customers with high resolution (1.7–4 m in optical range) remote information. The “Resource-DK” complex will transmit operational scanning information to ground based radio receiving stations. *Table 4* shows the main parameters of this complex, which is being constructed by the rocket-space center “CSKB-Progress” (Samara) (Milov and Kozlov, 1997).

The relatively new Russian MSK-4 (for multispectral observation in 4 spectral bands), AFA-TES, and TADA cameras, and the higher lens resolution western MRB and LMK cameras, are used for the aerial photographic observation of forest areas. These will be used in conjunction with the well-known Russian AFA-41/7.5, AFA-41/10, AFA-41/20, BAF-21, BAF-40, and AFA-TE-35 cameras.

Table 4: Main parameters of the future space observational complex "Resource-DK" (Milov and Kozlov, 1997).

Parameter	**Range of values**
Working orbits, km	450–600
Orbit inclination	64.8–71
Number of narrow spectral ranges scanned simultaneously	1–3
Spectral ranges, μm • Panchromatic • 3 spectral ranges (from working range 0.45–0.9)	 0.58–0.8 0.5–0.6 0.6–0.7 0.7–0.8
View band (from the height 500 km), km	640
View band in regime (from the height 500 km), km	40.5 or 27
Spatial resolution (in nadir from height 500 km), km • In panchromatic range • In one narrow spectral range • In 3 narrow spectral ranges Without compression • In transferring regime • In reproduction regime	 1.7 3–4 10 5 3–4
Radio channel data transfer rate, Mbit/sec	256

It is also possible to obtain information from non-photographic aerial observation methods, such as those given in *Table 5* (Korolev and Baranov, 1996b). These materials are useful for the investigation of atmospheric processes, ice conditions, and ocean conditions (Kravtsov and Kuzmin, 1997). This technique for ice cover detection was traditionally installed on AN-24, AN-30, IL-18, and TY-134-A aircraft laboratories (Kondratyev and Melentyev, 1995). Due to a variety of limiting factors (dependence on weather conditions at high latitudes, high cost of flying time, problems of information transfer and georeferencing, etc.), aircraft radar observation has now been replaced by all-weather satellites. Although space SAR has a lower resolution compared to aircraft based systems, there are benefits to using satellite SAR. These benefits include continuous observation, large view areas (e.g., the view band for "Ocean-01" is 460 km), and operational (real-time) transfer of data to customers.

Table 5: Parameters of non-photograph aerial systems (Korolev and Baranov, 1996b).

Equipment	Image Type	Spectral range	Geometrical resolution	Swath width (km)
"Nit"	Radar	2.25 cm	25×25 m	15–18
"Vulkan"	Thermal	3–5 μm 8–14 μm	6–7 arc minute	90
"Malahit"	Thermal	8–14 μm	5 arc minute	120

4 Remotely Sensed Data and Their Information Content

Scanning system images can be classified into space images (from satellites or space stations), aerial images (from airplanes or helicopters), ground-based images, and others (the latter is not considered here). Based on the spectral band,[1] they can be classified as ultraviolet, photo, infrared, radio, or thermal. Photographic images are those which are taken in the optical spectral band (wavelengths between 0.4–0.9 μm). Spectral signal images can classified as integral (in a single spectral band) images or multispectral (in several narrow spectral bands) images. In addition, images can be characterized according to their polarization (either horizontal or vertical). There is also a classification of images according to their geometrical and view parameters (e.g., type of projection, distribution of distortions, scale, spatial resolution, and informativity). *Table 6* shows the classification of images according to image scale (Knizhnikov, 1997).

Table 6: Classification of images according to scale (Knizhnikov, 1997).

Scale	Value	
	For air	For satellite
Large	1:1000	1:100000
Medium	1:10000	1:1000000
Small	1:100000	1:10000000

The territory of swath images can be divided into global, regional and local. This separation corresponds to the scale classification presented in *Table 6*. Small-scale

[1] The following relationship between between spectral bands and range of wavelength is given for reference purposes: the visible spectral range corresponds to λ=0.38–0.72 μm; near infrared (IR) to λ=0.72–1.3 μm; middle IR to λ=1.3–3.0 μm; and far IR to λ=7.0–15.0 μm.

images correspond to global level of observations; medium-scale images correspond to a regional level; and large-scale images correspond to a local level.

Images can be divided into three spatial resolution groups: low resolution (1 km or more), medium resolution (100–200 m) and high resolution (from less than 5 m to 30 m) (Danjulis and Zhirin, 1989). The resolution of space images is not as high as those of aircraft images, but space images have the advantages of natural generalization of surface images and large swath widths. This gives them an advantage for monitoring at the regional level.

The detail and information content of an image depend on the resolution (Rs) of the scanning apparatus. Low-detail images have a resolution of about 5 rows/mm and can be increased 2–5 fold. Medium-detail images have a resolution of about 10 rows/mm, and can be increased up to 10 fold. Images with a resolution of 20 rows/mm have the best geometric and viewing parameters, and can be increased 20 fold without losing information. Photographic images taken by high-quality cameras (such as KFA-100 or "Resource-F" cameras) have the maximum detail and information content for forestry applications. In addition, the 60% overlap of images allows their use for stereoscopic processing.

Scale is the main characteristic of aerial photographs. It is a function of the height of observation and of the focal length of the objective. The resolution of modern aerial photographic cameras is about 25–150 rows/mm for the AFA TE and MSK-4 cameras, respectively. The spatial resolution is 2–5 cm for MSK-4 and AFA-41 cameras, and as low as 5 mm for the AFA-TES camera. Aerial photographs have high geometric accuracy and are suitable for precise stereo measurements. Images at scales described in *Table 6*, as well as super large scales (1:2000 and more), are used for different forestry tasks.

Scanner images can be obtained in all spectral bands of the optical range, including the infrared thermal band. Modern scanning systems have high radiometric (brightness) resolution and provide images with a spatial resolution from several meters (from aircraft) to dozens of meters (from space). The information content of scanner images from the Russian satellite "Resource-0" is similar to the information obtained by the American LANDSAT (Garbuck and Gershenzon, 1997). As mentioned before, the main advantages of scanner images are short acquisition times and formats suitable for computer processing. In Russia, aircraft scanning was used only for scientific purposes, with no applied use in forestry.

The geometric parameters and image properties of radar images are not as good as photographic and scanner images. However, radar can operate independently of surface light conditions, meteorological conditions, and cloudiness. It also has faster operational acquisition rates and can generate images in a format appropriate for computer processing. Radar images have a high potential for investigations of high latitude forest areas and forest dynamic processes.

Primary radar data are generated in a form known as a "hologram", which makes it possible to synthesize images. To provide a constant scale image, it is necessary to make a geometrical correction of rows according to the distance and azimuth. Radiometric correction includes the correction of brightness. Thus, radar images have specific metric and brightness characteristics. Effective implementation requires the use of special software.

Synthetic aperture radar, by using satellite motion and Doppler shifting, can generate images with 10–20 m spatial resolution. This may be improved in the future to a resolution of several meters. Wavelength, polarization, and angle of incidence are also important parameters of radar systems. *Table 7* shows the main spectral ranges used in remote sensing.

Table 7: Frequency ranges of radar systems (Korolev and Baranov, 1996b).

Parameter	**Windows of transparency**	**"X"**	**"C"**	**"S"**	**"L"**	**"P"**
λ,cm		3.1	5.7	10	23	72
ν,Hhz		9.6	5.3	3	1.27	0.42

To improve the information content of radar images, one can apply different types of the polarization of the electromagnetic signal. For example, images from the "Almaz-1A" satellite have horizontal polarization for both transmitted and received signals. Radar data from the planned satellite "Almaz-1B" will have both horizontal and vertical polarization.

The angle of incidence, or the vision angle of the beam, is the angle between the radar beam and the vertical direction. The ability to change the angle of incidence allows the radar swath width to be increased. This increases the periodicity of the observation of the same landscape. Changing the angle of incidence while holding the frequency and polarization constant can improve the information content of the image and provide additional characteristics of the surface structure (e.g., vegetative cover).

Air and space observations in optical and near IR spectral ranges are recorded on black-and-white panchromatic and infrachromatic films, on color spectrazonal (pseudocolor) film, and occasionally on natural color films. The main shortcoming of panchromatic films is the low contrast of tree species during the summer season, which decreases their usefulness for detecting different types of forest vegetation. Therefore, the reliability of the interpretation of tree species and of forest area contours using such images is relatively low. However, the borders of non-forest lands and unforested areas, as well as forest stands which differ significantly by their age and stocking, can be reliably identified by the tone and structure of the image. The widespread birch and pine species in the taiga zone have a low contrast. Summer images are visible in the spectral range due to homogeneous soil-vegetation communities. Forested areas with similar age and stocking can be only separated from each other by ground surveys (Danjulis and Zhirin, 1989). Similar conclusions were made for analysis of the information content of declassified super-high resolution space images taken by KBR-1000 cameras (Sukhikh and Zhirin, 1996).

Infra-chromatic films, having two areas of sensitivity (in blue and near IR spectral ranges), increase the contrast of images of the tree species, especially coniferous and deciduous species. Therefore, these films are preferable for identification of differences in stand species composition. Information from colored spectrazonal space and aerial observations are the most informative under applied conditions, and are traditionally used for the determination of forest vegetation. The Russian two-layer aerial films SN-6M and SN-8 are used for the aerial photography of forest stands. Experiments have also been conducted on the use of the three-layer spectrazonal film SN-15.

In the interpretation of aerial and space images, forest objects are recognized by a complex of "direct" and "indirect" interpretive features. Direct features are those which can be directly represented and perceived by the interpreter: tone, color, shape, size, location, structure, and texture of images. Specific conditions of sites (landscapes) are used as indirect decoding features.

The information content and quality of the image is impacted by a wide variety of factors, including the specifics of the landscape, the scale of the image, the resolution, the type of photographic material, the spectral zones and the conditions of the observation. On super-large scale aerial photographs (1:2000 and larger), images show the crowns of trees, their shadows, and the background. Images at such a scale make it possible to recognize separate branches, shape of crowns, and their morphological features, which allows the determination of tree species and the degree of damage by pests, diseases, or other unfavorable factors. Landscape features do not significantly affect the image, because even small units of natural-territorial complexes are significantly larger than the areas shown in the large-scale images. Practically all trees with crowns outside the shadow of neighboring trees in the upper part of the crown cover can be identified and accounted for on these images. On large scale aerial photographs (1:2000–1:10000), the image can display a generalized pattern of the tree crowns forming the structure of the cover. Groups of trees are visible on the aerial photographs at medium and small scales (1:10000–1:100000), and the crown structure can be clearly interpreted.

Space images display large areas of forests with different groups of species (e.g., coniferous and deciduous) or separate tree species, depending on the scale of the image. Other features than the scale influence the image. These include specifics of the relief, the hydrographic network, the geological structure and the degree of industrial development of the territory.

Geometrical and figurative properties of the image change during the transition from one scale to another. While one can see crowns of trees in the large and medium scale images, a generalization of color and structure is typical for small-scale images. This is particularly true for space images. Small objects, with low contrast to background, become invisible as the scale is decreased. Contour outlines are generalized due to the exclusion of small details and curves. Eroded boundaries (i.e., zones of gradual transition) become clear, and are near to linear in the small-scale images. With decreased scale, the image is determined by the structure of the natural-territorial complexes of different landscape taxonomies.

With a sufficient overlapping of space photo images and with proper rules for making the aerial images, it is possible to construct a stereoscopic model of the observed territory. In addition to the decoding signals mentioned above, the stereoscopic interpretation of images makes it possible to determine the height of canopy layer and to separate stands of different average height. These signals allow the separation of forested areas from unforested areas and non-forest lands. The set of different interpretation signals serve as a basis for interpretation of aerial photographs in forest inventory and monitoring. High altitude space scanning increases the difficulty in making measurements in the stereoscopic model (Dmitriev *et al*., 1989). In this case it is impossible to measure the height of the canopy. However, stereoscopic decoding is useful for identification of forest land cover categories. *Table 8* summarizes the interpretation features of aerial and space images used in forestry and forest management (Danjulis and Zhirin, 1989).

The information given in *Table 8* indicates that different remote sensing images are useful for forest ecosystem surveying and monitoring. Customer requirements for this information depend upon the specifics of the problem studied, the size of the territory investigated, the intensity of forest management, the specific characteristics of the forests, and the landscape structure. Therefore, evaluation of the decoding potential of remotely sensed information should be done on the basis of the planned remote sensing application. Implementation of remotely sensed data with surplus information complicates the work, but lack of the information can lead to loss of quality and increased prices due to increased labor costs and due to expensive additional field observations. The experience and qualifications of the personnel carrying out the decoding, as well as the methods and equipment used, strongly impact the final result.

Although there are few examples of using the thermal and radio bands for forest ecosystem monitoring, this technology has the potential for greater development. These technologies, along with digital multispectral methods, are now among the most quickly developing and promising methods in remote sensing. Radar images can be provided in a spectral range with wavelengths ranging from centimeters to meters. The method provides a sensitive measure of the surface geometry and moisture. Deep shadows (due to objects with significant altitude differences) are typical for radar images. The length of the shadow depends on the angle of the incidence of the radar beam and on the difference in height between objects. The difference in height is more clear for small values of incidence angles due to increased length of the shadow. The length of the shadow can be measured directly from the image or by the use of a stereo model, and makes it possible to calculate, taking into account the image scale, the height of objects in the image. The level of detail achievable by decoding the objects in radar images depends on the resolution.

Table 8: Decoding possibilities of aerial and space images in forestry
(Danjulis and Zhirin, 1989).

Spatial resolution 250 m	
0.5 sq. km[1] 25 sq. km[2] 1 sq. km[3]	Contours of forest and non-forest areas, large rivers, lakes, burned out areas can be compared with details on 1:2500000–1:5000000 maps. Large tracts of pine, dark-coniferous, larch, deciduous forests. Thunderstorm and convective cloudiness. Trails of smoke from forest fires. Snow covered areas.
Spatial resolution 100 m	
9 ha[1] 4 sq. km[2] 25 ha[3]	Within forest reserve areas (details are similar to those of maps at scale 1:1000000–1:500000), unforested areas and non-forest land, including burns, bogs, and large clear cuts. On forested areas — coniferous of high- and low-productivity, soft deciduous forests.
Spatial resolution 25 m	
0.5 ha[1] 4 sq. km [2] 25 ha[3]	Forested areas (details are compared with those of maps at scale 1:500000–1:200000) are divided by groups of dominant species, types of site conditions, density. Unforested areas: burns, clear cuts, grassy glades. Non-forest lands: bogs, water, agricultural lands.
Spatial resolution 10 m	
0.04 ha[1] 16 ha[2] 1 ha[3]	Within forested area (details are compared to those of maps at scale 1:100000–1:50000): groups of dominant species, groups of types of site conditions, age groups, groups of stocking. Unforested areas: burns, cut areas, sparse forests, glades. Non-forest land: arable land, water, bogs, rocks, settlements, roads, etc.
Spatial resolution 3 m and better (aerial photographic images)	
0.01 ha[1] 1 ha[2] 0.1 ha and larger[3]	Details are compared to those of maps 1:50000 and larger, including: groups of species, average height, stocking, growing stock, type (group of types) of forest.

[1] Areas of a high contrast, for example, forests among non-forest areas, as well as non-forest territories among forests — 3×3 elements of resolution.

[2] Minimum area which is relevant to be separated on the original (contact) image is 2×2 mm.

[3] Minimum area which is relevant to be separated on the 4 fold increased image.

In radar images, large forest areas differ from unforested areas and non-forest land by the texture and structure of images. Agricultural lands, bogs, roads, harvested areas, and rivers can be recognized. Unforested areas such as grassy glades and burns can be recognized in both summer and winter radar images.

Experimental results, based on the analysis of texture characteristics of tree species groups (e.g., coniferous, mixed, deciduous) in SIR-C SAR images from the "Shuttle", have led to the following conclusions (Zaharov and Nazarov, 1998):

- Recognition of tree species groups by texture characteristics is not efficient for C-band (λ=5.6 cm) regardless of the type of polarization.
- Texture characteristics provides reliable classification for L-band (λ=23 cm). HV polarization (horizontal for transmitted, and vertical for received signals) is preferable.
- Different scattering mechanisms of electromagnetic wave means that the informational-texture parameters of radar images depends on the wavelength for different forest groups. For shorter wavelengths (C–band) the leaves and small twigs in the tree crowns play the main role. At this resolution, crowns of deciduous and coniferous trees create a compact cover. L-band radio waves are reflected from larger twigs and stems of trees.
- Differences in the morphology of deciduous, coniferous and mixed species result in differences in frequency distribution of image amplitudes and energy characteristics of the reflected signals.

Infrared thermal systems operate in both short wave and long wave ranges. Reflected and scattered radiance predominates for wavelengths less than 3 μm, and internal thermal radiance of the background surface predominates in the long wave band. Basic investigations of temperature regimes of forests shows that the temperature differences depend on the forest types (due to differences in moisture and drainage), and show that there is a sharp temperature gradient in the uppermost parts of the canopy layer. Therefore, the dynamics of temperature regimes of vegetation restrict the implementation of thermal images. Damaged, ill, and dead trees have the most stable temperature characteristics. This implies that there is a potential for the use of thermal images in detection of healthy, ill, weak, and dead stands.

At present, new computer technologies are providing opportunities to combine the advantages of radar and thermal images with those of optical and near IR images. The latter of these are the most useful for the determination of forest vegetation.

The scientific and experimental experience which has been gained in the implementation of remotely sensed information in the investigation of forest ecosystems in Russia indicate the relevant applications for remotely sensed information. The specifics of the application and the demands of customers (forest inventory enterprises, forest managers, nature protection experts, etc.) on the content, details, periodicity, and acquisition rate of images require the combination of different methods for receiving and processing information. For each application it is important to select the right combination of imaging, the scale of optimization procedures, the spatial and spectral resolution of images, the rate at which information is received, and methods for processing. During the last two decades the methodology for implementation of remote sensing in forestry has developed and been established. The main methodological principle is to use a systems approach for each application. Such a systems approach uses different steps for information collection and tools and methods for data obtaining and processing. Each technology typically has three data sources: satellite systems, aircraft systems, and ground observations. *Table 9* summarizes information on possible remote sensing applications in forestry and forest management, as well as requirements which must be met by remote sensing equipment and the required information content of remotely sensed data (Danjulis and Zhirin, 1989; Isaev and Sukhikh, 1986, 1991).

Table 9: Possible remote sensing applications in forestry (Danjulis and Zhirin, 1989; Isaev and Sukhikh, 1986, 1991).

Applications	Frequency of observations	Type of observation[1]	Spatial resolution, m	Bands			Space visual observa-tions	Ground investiga-tions
				0.4-1.1 µm	IR-thermal	SHR		
Natural-territorial division into districts (landscape, forestry-ecological), mapping and forest inventory								
Forest inventory and planning (protected zone)	10 years	II	0.5–2	+	-	-	-	+
• For intensive zone (repeated) with creation of maps at scales of 1:10000, 1:25000, 1:50000 • For extensive zone with creation of maps at scale of 1:25000, 1:50000								
1. Primary	-	II	1–2	+	-	-	-	+
2. Secondary	15 years	I	10	+	-	-	-	+
Inventory and mapping in the non-protected zone in the scale of 1:100000	20 years	I II	10–20 0.5–1	+ +	- -	- -	- +	- +
Small scale (1:200000–1000000) thematic mapping of forests	10–20 years	I II	10–30	+ -	+ -	+ -	- +	- +
Protection of forests from fire								
Control for fire danger (creation of express-maps for fire prognosis):								
• snow cover, phenology condition • humidity of combustibles	3–5 days	I	30–200	+	+	+	+	-
• synoptic situation, storm-clouds	3–5 days	I	30–200	-	+	+	-	-
Detection of centers of forest fires and control of their dynamics	2–3 times per 24 hours	II I	10–50 200–1000	- +	+ +	+ +	- +	+ -
• detection of forest fire centers, estimations of fire parameters	2–3 times per 24 hours	I II	10–200 1–10	+ -	+ +	- -	+ +	- +
• detection of convective cloudiness over fire areas	2–3 times per 24 hours	I II	200–1000 -	+ -	+ -	+ -	+ +	- -
• forecasts of fire development and control of dynamics	2–3 times per 24 hours	I II	10–200 5–10	+ -	+ +	+ -	+ +	- +

Protection from natural calamities, insects, industrial pollutants								
Control of insects, forest status in industrially polluted zones	Once per year	II	0.1–0.5	+	+		+	+
Exposure of plantations damaged by winds, insects. Estimation of damage, control, liquidation	Twice per year	I II	10–20 0.1–0.5	+ +	- -	- -	+ +	- +
Control of forest utilization and recovering								
Control of areas, volume and clear cut areas of final harvest	1 year (area of glades)	I II	10–20 -	+ -	- -	- -	- +	- +
Control of organization of harvesting in cutting-areas, utilization of wood, protection of young stands, on-soil cover (survey of cut areas)	1 year of glades	II	0.1–0.2	+	-	-	+	+
Control of the dynamics of reforestation on unforested areas	5 years (till 10 years old)	I II	10–20 0.1	+ +	- -	- -	- +	- +
Control of harvest and reforestation of valuable forests (for example, cedar).	1 year	I II	10–20 -	+ -	- -	- -	- -	- +
Account of current changes in forest reserve areas								
Account and mapping of current changes in the forest reserve area caused by:								
• forest fires;	1 year	I II	10–20 -	+ -	- -	- -	- +	- +
• natural calamities and other unfavorable factors, industrial activities	1 year	I II	10–20 0.5–1	+ +	- -	- -	+ +	+ +

[1] Types of observation: I — space; II — air.

5 Methods for Processing Remotely Sensed Data

The information needed for applied forestry problems and for the scientific investigation of forest ecosystems is obtained from images by photometric, photogrammetric and digital (computer) processing and interpretation. Photogrammetry provides the geometrical parameters, photometry provides the radiative (energetic) characteristics, and decoding yields thematic information on the object under study. Computer processing, earlier used for automated decoding, is now used for photometric and photogrammetric analysis.

Details of photometric and photogrammetric image processing have been described in many textbooks (Brukhanov *et al.*, 1982; Dmitriev *et al.*, 1989) and can be omitted in this review. It can be mentioned that photogrammetric methods allow us to determine the spatial location of objects in images, to determine the coordinates of selected points, and to develop digital models. Photometry is based on measurements of spectral brightness of natural objects. Statistical processing of brightness variation is used for further characterization of spectral and structural features used in the interpretation.

Image interpretation and computer processing are the most developed and widely distributed methods are used in remote applications to forest problems. Image interpretation can be divided into visual, measurements, and analytical interpretation. Visual interpretation remains the most intensively used method for forest remote sensing applications. The interpretation process usually follows two steps. The first is the "reading" of images, in which the borders and location of objects are determined based on a set of decoding signals. This is followed by the interpretation of images, in which the classification of the objects is analyzed and specific parameters are estimated. The quality of the image interpretation depends mainly on the qualification of personnel performing the interpretation, including their experience, their knowledge of the landscape and conditions of forest vegetation in a given territory, and their ability to select and use landscape signals. Methods for visual interpretation of forests with aerial and space photographic images have been developed and improved over several decades. The development of the concept of forest interpretation as a distinct scientific discipline should be credited to Professor G.G. Samoilovich and his scholars from St. Petersburg Forest-Technical Academy. Forest interpretation is an analytical process involving the investigation of photographic images, the detection and determination of forestland categories, and the quantification of biometric indicators of forest stands.

Various natural and technical conditions affect the creation and quality of images. Natural conditions include the season and time of the observation, optical parameters (brightness of surface, height and azimuth of the sun during the observation, cloudiness) of the atmosphere, spectral characteristics of forest stands, and so forth. Technical conditions include the type of scanner platform, the speed and height of the flight, the height and inclination of the satellite orbit, the basis of observation, the parameters of the scanner (lens parameters, focal length, resolution, etc.), the type of film (resolution, spectral and sensing characteristics), and the details of the photochemical processing of the film (the process of making negatives and positives, type of photographic paper, etc.). The picture of different land categories and forest stands obtained from an image could be different for neighboring passes or even within the same image because of the influence of many factors. Visual decoding based on the interpretation features makes it possible to detect "noise" due to the above mentioned factors.

Forest interpretation of aerial photographs is divided into forest management and forest inventory interpretation. The first is provided for observation of non-forest lands and unforested areas, forests damaged by different causes, forest plantations, harvested areas, etc.; the second — for forest inventory (Dmitriev *et al*., 1989). Forest inventory interpretation consists of contour (polygons) identification and forest taxation assessment. Contour decoding includes the reading of images, the determination and drawing of the borders of both forest land cover categories and primary units of inventory, and the identification of exact locations of objects. Forest taxation assessment decoding is used for analysis and interpretation of images and for determination of quantitative and qualitative characteristics of forest stands. These characteristics include the species composition, the stand height, the canopy layer closure, the stocking, and the age structure.

Decoding features can be divided into the following classes:

- Photometric features that include tone (on black and white) or color (on spectrazonal and multispectral) images; they register differences in spectral radiance reflectance of forest vegetation and other objects;
- Morphological features that describe both the structure and canopy layer picture of stands, the size of crowns and gaps between them, etc., as well as the structure of unforested areas, and,
- Landscaping features that reflect existing regularities in the location of forest objects, especially types of forest site conditions and dominant species connected to landscape structures.

Detailed descriptions of photometric and morphological features for the interpretation of forest vegetation, as well as methods for landscape investigations in decoding of aerial and satellite images, can be found in numerous publications (Sukhikh and Sinitsyn, 1979; Danjulis and Zhirin, 1989; Dmitriev *et al*., 1989; Kireev, 1977; Samoilovich, 1964; Sukhikh, *et al*., 1977).

There are a number of reasons for replacing traditional decoding methods by computer methods. These include the availability of advanced computer techniques and software, the wide use of remotely sensed data in digital form, improved access for customers, the large amounts of initial information, the complications in visual analysis of large data sets, and the demand for operational forest monitoring at the regional level. Nevertheless, the complete replacement of visual interpretation of forest objects by computer decoding is neither possible nor relevant. Many interpretation features used by experts in forest vegetation identification cannot yet be formalized. Therefore, a combination of these two types of analysis is considered as the best method for remote sensing applications in forestry today.

The search for efficient computer methods was initially oriented towards automated interpretation of forest inventories in remote unused forests (Sukhikh *et al*., 1982; Elman, 1984). This research demonstrated that good results could be achieved if operator and computer worked in an interactive mode. The operator provided stratification and contour decoding of the images, and estimation of assessment indicators was performed automatically. The operator controlled the analysis process and could interrupt the process to change its direction and make corrections. Algorithms were developed for geometric and photometric transformations of images, filtration and statistical processing, identification and parameters estimation, and others. As a result, a software library for interactive image processing was established. Based on this experience, the Automatic System for Air-Space Information Processing in Forestry (ASASIP) at the AUA *"Lesproekt"* was developed (Bodanskii *et al*., 1984; Elman *et al*., 1984).

Methods for automatic processing of remotely sensed information and the ASASIP approach have been significantly improved. Many of these methodological approaches are still in operation in spite of the rapid development of modern software for image processing. Among these former approaches are:

- The method for estimating forest taxation indicators of stands in small-scale aerial photographs by using the set of photometric properties of features in the test sites. This method was used for inventorying the remote unused forests in Yakutiya.
- The method for estimating forest taxation indicators in large-scale aerial photographs. This method includes an interactive approach for estimating the canopy closure, the number of trees per unit area, the average crown area, and other required indicators. The method has been applied in inventories of tree and shrub vegetation of deserts (Breido and Zhirin, 1989; Zhirin, 1991).
- The method for determination of land cover categories and groups of species on scanner images. This method includes the following steps: (1) filtration, contrasting and synthesizing; (2) clustering and color selection; and (3) segmentation. This approach used the scanner space image "Fragment" for European Russia.

In spite of restricted practical implementation of automatic image processing, most of the methods have not changed in a mathematical sense during the last decades and are now used in commercial software.

Today, there is no image processing for practical forestry in Russia. Some limited work is conducted in scientific and research projects at the Center on Problems of Forests Ecology and Productivity (CPFEP) RAS, the SBRAS Forest Institute, and "VNIIClesresurs" of the Federal Forest Service of Russia.

The main principles for computer processing of remotely sensed data are (Baranov *et al*., 1997; Korolev and Baranov, 1996b):

- Preliminary analysis and treatment. This includes geometric correction, spatial identification, georeferencing of images, and transformation of data into the appropriate map projection for further work. During the transformation, a geometric transformation of images and counting of pixel values on a new raster grid is performed. An alternate approach is: decoding the image, vectorizing of contours, creation of maps and a GIS, and matching the image to real coordinates and transforming it to an adopted map grid (Malysheva *et al*., 1997a,b).
- Correction of images with respect to radiometric, spectral, and frequency characteristics. It includes the improvement of brightness and contrast, and normalizing the brightness in order to generate images suitable for decoding.
- Thematic analysis. This includes separating (or delineating) the objects in an image, identifying them, and analyzing their dynamics by using time series of images. Software for the remote information decoding has the following standard operations for thematic analysis: arithmetic (addition, subtraction, multiplication, and division of images into integer numbers); logical (conjunction, disjunction, equivalence, inversion, negation); filtration; masking; statistical estimation; and classification with and without education (Baranov *et al.*, 1997; Korolev and Baranov, 1996b).

Today, commercial software adapted by customers for specific forestry investigations is more often used for remotely sensed data processing. Examples are ERDAS Imagine, ARCINFO and IDRISI (CEPL RAS), IDRISI and EPPL-7 (Forest Institute SBRAS) (Vaganov and Petrenko, 1997), IDRISI and TOPOL (VNIIClesresurs). The latter software was developed by the Czech Forest Service. It is an advanced variant of earlier products by AUA *"Lesproekt"*.

6 Inventory and Mapping of Forests by Remote Sensing Methods

There were three major types of forest inventory in Russia during the last 50 years: forest inventory and planning (FIP-*lesoustroistvo*); remote sensing based inventory of remote forests; and air taxation (Shvidenko and Nilsson, 1997). The first two are the basic methods now. Currently, FIP in Russia is carried out by on-ground assessment methods together with the interpretation of medium scale (1:12000 to 1:15000, and sometimes up to about 1:30000) aerial photographic (primarily spectrazonal) images. The level of detail of FIP methods ranges from Category I (the most detailed) to Category III (the least detailed). Field inventory work is repeated every 10 to 15 years using the same technology in every forest enterprise (there about 1900 forest enterprises in Russia). The forest inventory manuals allow the use of spectrazonal and black-and-white aerial photographs at the scales of 1:15000 for FIP categories I–II and 1:25000 for FIP category III (Instruction on Forest Inventory…, 1995; Investigation on Characteristics…, 1998).

Forest managers and forest inventory experts have recently concluded that the methods for inventorying the forests in Siberia and the Far East should be improved by the application of small scale aerial photography. The new technology should meet the following requirements:

- provide an inventory accuracy equivalent to FIP category III (*razrjad lesoustroistva*);
- use aerial photographs in the scale of 1:15000 to 1:25000; and
- be more cost effective than the traditional forest inventory.

Besides the optimization of the initial scale of aerial photographs, the decreased costs are assumed to be achieved by decoding photo negatives and by a transformation of data to digital image processing methods, which should replace the traditional technology of decoding contact aerial photographs (Kukuev, 1998).

Investigations made in the 1980s made it possible to improve the repetetive forest inventory by updating the forest taxation data based on spectrazonal satellite images with 5–10 m resolution and with data from previous inventory. It was intended to implement this forest inventory technology in the extensively managed taiga forests of the European North, of Western and Eastern Siberia and the Far East which were earlier inventoried by on-ground FIP category III methods. The basic idea of the new technology is to interpret the land categories disturbed during the period between two inventories by human interventions and natural calamities (harvested areas, burns, sparse forests, wind damaged forests, etc.). Space photo images or aerial small-scale photos are increased to the scale of 1:50000, the scale used as the basis for the district forest maps. Areas of forest plantations, thinning, and selected sanitary felling are also delineated on the images. In the field assessment, characteristics and boundaries of stands (primary units of forest inventory — PUFI) which have changed during the revision period, are assessed by measurements. Characteristics of those PUFI with no changes of boundaries are reassessed. In this process, the stand forest taxation indicators of the previous forest inventory (age, average height and diameter, and growing stock) are updated based on yield tables and growth models. These latter models are based on experimental studies and measurements in inventoried forests. The technology has been evaluated and was approved as the new inventory approach in 1986–1987.

The photo statistical method in forest inventory is primarily used in remote unmanaged and unused forests (*reserved forests* in Russian terminology) in the North and North-Eastern regions of Russia. This method has not changed during the last two decades and is still widely used in forest inventory practice (Sukhikh *et al.*, 1982). The Moscow Aerospace Expedition and North-Western Forest Inventory Enterprise currently use this scheme for inventorying 10–20 million hectares per year.

The complete cycle of a photo statistical inventory involves a 4-step stratified sampling scheme. The first step is a complete contour and forest taxation interpretation of spectrazonal space images at the scale of 1:270000 (satellites “Kosmos” and “Resource-F”). For each PUFI a land cover category is defined. For forested areas, dominant species or group of species, age group (usually 2–3 groups are identified, e.g., young and middle-aged *vs.* immature, mature and overmature stands), the site condition group, the site index class, and the relative stocking are assessed. The PUFIs are combined into strata for which sampling schemes are developed. The extent and distribution of samples are defined based on the requirements of the inventory manual to provide a mean standard error of the average growing stock of the inventory object within the limits of ±2% at the 0.95 confidence level. The systematic error should be not more than 3%.

The second step of the inventory uses aerial photographs at scales of 1:7000–1:10000 which are systematically distributed to cover 5% of the inventoried territory. The identification of the contours and the assessments are carried out for each PUFI within the inventoried (5%) area. In the interpretation of strata, the following indicators are usually assessed: species composition, age class, forest type, site index, and relative stocking.

The third step includes measurement of separate stands in photo test areas. They are randomly or systematically distributed by strata based on sampling schemes, with approximately one photo test area per image. The average height, crown diameter, clarification of species composition, age class, site index and stocking are measured in the photos. Average diameter and growing stock are assessed based on available regressions for different stand indicators.

The fourth step comprises on-ground field measurements of part of the photo test area. This covers 5 to 10% of the total number of the photo test areas. This stage assesses the relationship between forest taxation and interpretation indicators, estimates the accuracy of interpretation, and provides data for eliminating systematic errors.

A modified photo statistical method, which has been tested by the North-Western Forest Inventory and Planning Enterprise, is used to estimate the area and growing stock of mature and overmature stands of different dominant species. The objective is to provide better information for planning and organization of the final harvest. As a result of this work, it has been estimated that the difference between traditional forest inventory data and the photo-statistical method is some ±10% for growing stock of mature and overmature forests. The total costs of the traditional methods of forest inventory is twenty times as expensive as the modified photo-statistical method (Arkhipov *et al.*, 1992).

Similar technology was used for inventory of desert woody-shrub vegetation. The technology has the following features. A territory stratification is provided using black-and-white space photographic images. The interpretation is carried out on large scale (1:1500–1:2000) aerial photographs. The necessary number of samples is calculated based on the spatial variability of the growing stock of desert woody-shrub vegetation (Zhirin, 1984; Technical Instructions on the Inventory…, 1985).

It has been shown that the interpretive potential of high-resolution (2m) black-and-white space photographs is sufficient for applications in forest inventory in zones of intense forest management (Sukhikh and Zhirin, 1996). For inventory of recreational areas, it is necessary to conduct highly detailed investigations of objects. This can sometimes be extended to the level of the description of individual trees. The use of large-scale aerial photographic images was experimentally tested in areas defined by inventory manuals as “historical memorial natural museums” and reserves. It was shown that for the inventory of recreational forests, it is satisfactory to use spectrazonal aerial photographs at the scale of 1:2000 to 1:5000. These, combined with black-and-white aerial photographs at the scale of 1:500 to 1:1000 taken during the spring and autumn periods, make it possible to supplement assessment characteristics of forests and to define the height, coordinates, and crown diameters of trees, the species composition, to identify valuable trees, and to lay out landscape designs (Bakhtinova and Fedorov, 1987).

Development of forest maps based on remote sensing materials comprises a large field of applications with a wide variety of thematic maps. These maps differ by purpose, scale, and content. Traditionally, small-scale maps are created on the basis of cartographic materials produced by the forest inventory at the scale of 1:50000–1:200000. Content generalization (e.g., boundaries of PUFI and forest taxation characteristics of aggregated forest inventory units) is typically subjective. Interpretation of satellite images is based on the similarity of spectral, structural and texture signals of different areas. Due to the natural generalization on the images, information can be transferred from images to the original map. This avoids the oversimplification of contours that occurs in traditional technologies in the transition from larger to smaller scales. The content of maps based on space images thus can become more objective and accurate. Moreover, forest vegetation in space images is shown together with other ecosystems. Forests are among the most easily recognizable objects in space images, and have intrinsic regularities in their composition and interactions between components. The use of remote sensing information therefore improves the potential to evaluate the ecological role of the forests. This is illustrated in ecological mapping as a new field of forest cartography (Pleshikov *et al*., 1996b; Malysheva *et al*., 1997b).

The first maps of forest reserve territories based on multispectral satellite images at the scale of 1:1000000 were included in the Atlas of Mongolia (1980). Based on field experiments, the methodology for small-scale mapping was evaluated and approved (Sukhikh *et al*., 1981). Small-scale maps of forest reserve areas include the following elements: dominant species in the forest, accompanying species, age groups, stocking groups, unforested areas, and non-forest lands.

The methodology for forest landscape mapping began to develop in the 1980s (Kireev, 1992). Many maps of this kind have been produced (Landscape Methods in Forest Mapping, 1987). The SBRAS Forest Institute later significantly improved the landscape approach for forest ecosystems investigations and used these improvements to compose special maps. A complex approach for the investigation and mapping of forests was realized by dividing landscapes into different hierarchical landscape units based on space images. For instance, the following maps, at scales of 1:200000 to 1:1000000, have been developed based on a landscape approach and satellite images (Furyaev and Kireev, 1983; Landscape Methods in Forest Mapping, 1987; Rjapolov, 1985; Isaev *et al*., 1991; Kalashnikov *et al*., 1991):

- forest soils;
- forest types;
- current land-use/land-cover of forest lands;
- forest combustibles;
- disturbance of forest by fires;
- non-wood forest products;
- hunting areas;
- forest entomology.

The development of ecological forest maps is typical of current methodologies for landscape analysis. Integration of remote data with different types of forest information on a unified cartographic basis in a GIS environment gives new dimensions to forest ecological mapping. Some results reported by the SBRAS Forest Institute on mapping of forest disturbances on a landscape basis were based on space images at scales from 1:100000 to 1:200000 (Pleshikov and Cherkashin, 1996). Mapping of the forest cover transformation was made for the central part of Siberia at a scale of 1:2500000. Detailed ecological maps at a scale of 1:25000 were produced for key areas of Middle Priangarie, Minusinskaja Kotlovina, and the Near-Enisei region of Western Siberia. These maps characterize the actual and potential productivity of the ecosystems and the restoration dynamics of forest vegetation communities after disturbances (Pleshikov *et al.*, 1996a).

Using a similar approach, a joint Russian-American Project has employed remotely sensed data aimed at the development of a rational land use policy for sustainable development of the Baikal region. Combining remote data and GIS-technologies, agricultural and forest lands at a scale of 1:50000 to 1:100000 were mapped for the Kabanskii district of the Burjatija Republic (Miheev *et al.*, 1996). Systems analysis of different time series of photo images from “Resource-F1” and multispectral scanner information from “Resource-01” allowed the estimation of the diversity and fragmentation of landscapes, the degree of transformation, and the assessment of economic and environmental value of forests and arable lands.

Thematic mapping of forests has traditionally been performed at the AUA *“Lesproect”* and was later done at the *VNIICLesresurs*. This development is based on remote sensing information and includes three main objectives for the thematic cartography: inventory, estimation and forecasting, and operational needs. Mapping conducted in support of forest monitoring typically addresses these three objectives (Kalashnikov *et al.*, 1991; Kalashnikov and Pleshikov, 1991).

The inventory mapping includes maps of woody-shrub vegetation at a scale of 1:300000, maps of the current forest state (1:100000), and maps of the state of exploitable forests (1:50000). The methodology for generating these maps is part of the forest inventory in Russia.

Maps for estimation and projections (e.g., maps of the resistance of forests to storms and of the probable distribution of areas affected by *Dendrolimus sibirica*) at a scale of

1:100000 (Malysheva and Sukhikh, 1991) are used by the Western Special Forest Inventory Enterprise.

Operational maps are necessary for the monitoring of permanent changes in forest reserve territories, the control of harvested areas, the state of reforestation in clear cut areas, and the status of forests in polluted zones (Kalashnikov *et al*., 1991). These maps provide for detection and estimation of dynamics of forest due to natural disturbances and industrial activities.

Methodologies for the development of forest ecological maps (Malysheva *et al*., 1997b) and of maps of the state of forests (Malysheva *et al*., 1997a) have been reported recently. The methodologies were tested in the production of a series of maps for the watershed area of Lake Baikal at the scale of 1:1000000. This series include maps of forest cover transformation, forest stability, and the current state of forests in the region. Spectrazonal photo images at a scale of 1:270000 from "Resource-F" and/or high resolution MSU-E scanner images are the main sources for these maps. The analysis of scanned materials was carried out by visual and automatic methods. For example, about 300 space images at the scale of 1:1000000 were visually interpreted in order to establish the current state of forests in zones established for the protection of the water of Lake Baikal (Malysheva *et al*., 1997a). The interpretation of space images was conducted in the following manner: identification of forest and non-forest lands; separation of forest lands into forested and unforested areas; classification of forested areas by dominant species, and level of transformation by harvests and fires. The content of the maps includes the following elements:

- dominant tree species and shrubs;
- associated tree species;
- forests disturbed by fires and harvests in different years with the differentiation by species;
- unforested areas;
- recent harvested areas and burns;
- non-forest lands.

These maps show the regularities in the distribution and growth of forests, and characterize the structure of species and degree of disturbances caused by anthropogenic and natural factors.

7 Investigation of Forest Ecosystems

This chapter presents a review of basic research, which has not yet been practically applied, as well as some results of investigations within scientific projects.

Investigations of the spectral reflectance of forest vegetation is one of the basic components in the analysis of remotely sensed data. Such research is focused on detection of forest vegetation damage at very early stages, identification of the most informative spectral bands for forest applications, and increasing the information content of remotely sensed data. The development of new remote sensing methods has always been based on studies of the spectral reflectance of natural objects. The study of the optical properties of landscapes was initiated by E.L. Krinov in the 1940s (Krinov, 1947). His spectrometric classification of natural objects has since become classic. The increased availability of spectrometers and spectropolarimeters with high spectral and spatial resolution further encouraged investigations in this direction.

Spectral characteristics of forest vegetation can serve as an indicator of their physiological state, disturbances of cell structure of plants, and pigment composition. Industrial pollution and other unfavorable factors cause physiological stress and interference with normal plant metabolism, which in turn influences the pigment concentration and cellular structure. The dependence of spectral characteristics on the physiological state of the vegetation, particularly in the visible and near IR spectral ranges, is important for remote diagnoses of vegetation health.

Studies of the spectral properties of forest vegetation has continued over the last few years (Isaev and Pleshikov, 1987; Vygodskaya and Gorshkova, 1987; Zhirin *et al.*, 1995; Ress and Willams, 1997). There are some interesting results in studies of spectral brightness characteristics of ecosystems in areas of industrial pollution on the Kola Peninsula (Monchegorsk, Apatity, Kirovsk). These investigations were made by the RAS Institute of Geography within the framework of an international project organized by Moscow State University in 1994 (Kapitsa and Golubeva, 1995). The main goal of this research was to identify and to classify the forest-tundra vegetation by type, species composition, and state.

Measurements were made by a video spectro-polarimetric system of high spectral and spatial resolution from ground stations and from an MI-2 helicopter. The spectro-polarimeter provides 450 values of spectral brightness in the 0.38–0.83 μm range, with a 0.001 μm resolution. The spectro-polarimeter is synchronized with a color TV image. Spectral measurements were made in two regimes. The first regime had a spatial resolution of 1.2 m×1.2 m and the second had a spatial resolution of 20 m×20 m. Special software was used for hyperspectral data analysis. It was based on data reduction algorithms and evaluation of typical spectral features in narrow spectral intervals. Both two-dimensional and multi-dimensional cluster analysis were used to classify forest-tundra vegetation by their spectral characteristics. As a result, the cluster analysis of spectral characteristics of tundra patterns showed 7 main types of forest-tundra vegetation, with different proportions of lichens and small shrubs, based on observations from ground stations. Eleven types of ecosystems were identified during the flight experiments. Two classes of ecosystems damaged by human activities were identified: technogenic waste lands and forest-tundra with high cover vegetation damage (Kapitsa and Golubeva, 1995).

Spectral characteristics of needles in stands impacted by urban atmospheric pollution in Moscow, and industrial pollution near large industrial regions in the Southern part of Western Siberia (Sajany), have been studied. These results allow a rough diagnosis of the state of trees and a reliable determination of whether trees are healthy or weakened. Measurements were conducted by the high resolution (0.3–0.8 μm) spectrometer "Kvarz-4" in the spectral range of 0.415–0.85 μm. It was confirmed that normalized differential vegetation index (NDVI) allows a more reliable classification of forest state than other spectral parameters (Zhirin *et al*., 1995).

NDVI was initially used for the estimation of vegetation phytomass. It is currently implemented in different applications, such as the analysis of the dynamics of vegetation cover at the global level (Antonovsky *et al*., 1992), the study of phenology of forest cover and peculiarities of natural and territorial complexes of landscapes (Zhirin *et al*., 1996), research on dynamic processes in boreal forests (Bartalev *et al*., 1995), investigation of the dynamics of the destruction of pre-tundra forests caused by emissions from the Norilsk group of enterprises (Kharuk and Vintenberger, 1995), and assessment of depressed forest vegetation near the Chernobyl Atomic Station (Efremenko and Moshkov, 1997). For a more precise identification of areas with depressed vegetation, the authors of the latter paper proposed a 3-channel vegetation index TCHVI with an additional signal in the green (GR) zone (Efremenko and Moshkov, 1997). This index is defined as follows:

TCHVI = (RED-GR)-(NIR-RED) / |RED-GR| + |NIR-RED|

This can be compared with the NDVI index, defined as:

NDVI = (NIR-RED) / (NIR+RED),

where NIR is the value of the signal in near IR zone (0.73–1.1 μm), RED (0.58–0.68 μm) and GR are signals in red and green zone of optical range respectively. An examination of eighteen different vegetation indexes showed that the 3-band approach has clear advantages for identifying stressed vegetation (Chimitdorzhiev, 1998).

Scientists from the SBRAS Forest Institute have investigated forest ecosystems by remote sensing methods on a landscape basis. This approach includes studies of ecological regimes of taiga ecosystems and their dynamics (Konstantinov and Gorozhankina, 1991); diagnostics of forest growth conditions and forest productivity (Pleshikov *et al*., 1991; Sedykh, 1991); studies of natural and antropogenic processes causing species changes (Pleshikov and Ryzhkova, 1991; Sedykh, 1991); determination of fire danger and forecasts of the distribution of forest fires (Valendik and Sukhinin, 1991); studies of the post-fire dynamics of forest ecosystems (Furyaev, 1991); and forest entomological monitoring (Isaev and Sukhikh, 1991). The most active efforts are oriented towards the development of strategies and methodologies for forest fire protection based on remote sensing information. During the last decade, these activities have relied increasingly on GIS technologies (Valendik, 1996; Stocks and Goldhammer, 1997). Predictions of forest fire danger are provided by the SBRAS Forest Institute, together with the Krasnoyarsk Association *"Avialesohrana"* and the SBRAS Computational Center, based on weather conditions provided by NOAA (Pleshikov *et al*., 1996a).

Data collected by long term investigations of scientific groups from the SBRAS Forest Institute, using remotely sensed data in combination with forest inventory data, served as an information base for the development of a three-layer GIS titled "Forests of Middle Siberia" (Pleshikov *et al*., 1996a; Vaganov and Petrenko, 1997). This GIS consists of four subsystems with different purposes:

- Monitoring of the dynamics of forest cover transformation, forest management activities, and state of reforestation;
- Estimation of technogenic impacts on forests;
- Monitoring of the population dynamics of dangerous insects; and
- Forest fire control.

Interesting results have recently been reported by a joint Russian-American project on the characteristics and sustainability of boreal forests. The joint research has demonstrated the potential for using unclassified remotely sensed information obtained from national security systems in Russia and the USA in combination with data from civil satellite systems like "SPOT", "Landsat", and "Resource-F" for monitoring boreal forests. The investigations were conducted at test sites in the Moscow region and Krasnoyarsk Krai in Russia, and in Central Alaska (Fairbanks) in the USA. Experts from both countries have developed several products based on high resolution images without any access to ground truth information on forests at these test sites. These results identified data gaps which could be filled in by remotely sensed data from national security systems. For example, these latter data can be used for:

- increasing the level of detail of land cover category maps based on "Landsat" space images;
- increasing the accuracy of the assessment of forest stand characteristics such as species composition, canopy closure, crown diameter, and height groups;
- analyzing long term forest cover dynamics by using large amounts of archive data (national security organizations began remote sensing observations of the Earth in 1960, much earlier than civil agencies). These results are interesting for estimation of the carbon budget of forest ecosystems; and
- increasing the accuracy of estimates of forest damage by insect outbreaks (Project on Studies of Characteristics…, 1998).

During the last years, many interesting examinations of radar methods in boreal forests have been conducted using data from new western satellites. Using multiband polarized radar images, it has been possible to identify the amount of forest biomass and conduct mapping of forests (Le Toan *et al.*, 1992; Dobson *et al*., 1992; Ranson and Sun, 1997; Kharuk *et al.*, 1998). Although some publications state that the saturation occurs at relatively low values of live biomass (e.g., up to 30–50 $t \cdot ha^{-1}$ using the L-band from JERS-1 (Luckman *et al*., 1998)), appropriate combinations of longwave and shortwave bands under different polarization allow biomass estimation for levels up to 200 $t \cdot ha^{-1}$ for plain and hilly terrain (Kharuk *et al*., 1998). X-, C-, and L-bands of SIR-C/X-SAR with different polarizations in Western Sayan range and linear regression were used; Ranson and Sun (1997) received similar results in boreal forests in Maine, USA.

Results from the operational radar satellites ERS-1 and JERS-1 have shown sensitivity of the radar backscatter values to the freeze/thaw cycle, forest fire and logging, different forest land cover categories, etc. Using C-band data in combination with L-band data indicated a high potential for vegetation mapping. ERS-Tandem data generate interferometric coherence images which can be a useful tool for land cover classification and the generation of digital elevation models (DEM), and allow significant progress in forest inventory and monitoring (Schmullius and Rosenquist, 1997). It has been clearly shown by experiment that forests can be clearly discriminated from other land categories, and that a number of forest types can be identified. The forest mapping accuracy was more than 90%. The approach was based on the SAR interferometric correlation and the backscatter intensities using ERS-1 SAR repeat-pass data (Wegmueller and Werner, 1995, 1997).

While there are different opinions about the accuracy of data acquired from the AVHRR radiometer on American NOAA satellites, these data are widely used for different goals. The major reasons for this are: (1) the availability and low cost of data, and (2) the high periodicity of observations (two times per day, in four spectral bands). The positive conclusions were reached in studies of taiga landscapes (Zhirin *et al*., 1996).

Synergistic analysis of multiple sources of remotely sensed data has recently been used for a variety of goals: assessment of ecological situation and the degree of change due to air pollution and other anthropogenic factors of forest stress. For example, ERS-1/SAR and Landsat/MSS were used together with on-ground measurements of moss chemistry and bioindicators for forest classification, as well as for evaluation of forest ecosystem transformations in regions with unsatisfactory environmental conditions (Donchenko *et al*., 1998). Landsat MSS and Landsat TM data were successfully used to identify forest degradation in the Kola Peninsula (Regina, 1998).

8 Methods for Special Surveys of the State of the Forests

This chapter presents a review of methods and technologies based on remotely sensed data that are used in the framework of special surveys for estimating the dynamics of forest ecosystems impacted by abiotic, biotic, and anthropogenic factors. The term *special surveys* is used to identify forest investigations, apart from standard forest inventories, in order to meet management information needs and provide updating of forest inventory data.

These special investigations aim to:

- recognize and account for forest fire and natural disaster areas;

- provide for control of harvest and reforestation on harvested areas and burns;
- estimate the condition of forests damaged by insects, diseases, and industrial pollution;
- estimate the state of forests where there is intensive oil and gas extraction and exploration; and
- monitor forests designated primarily for landscape protection and recreation.

8.1 Forest Fires

The use of remotely sensed information can address two problems:

1. Detection and observation of forest fires by space images, allowing better organization of aircraft-based forest fire protection.
2. Estimation of burned areas and resulting damage.

Scientists from the St. Petersburg Forest Research Institute were pioneers in contributing to the solution of the first problem mentioned above (Artzybashev, 1974; Implementation of Satellite Information…, 1977). Low resolution operational scanner information (and later, medium resolution information from MSU-SK scanners on "Resource-01" satellites) was used for detecting the centers of large forest fires (more than 200 ha) by smoke trails. However, lack of sufficient resolution in the space images did not permit the timely detection of the subsequent extinguishment of forest fires. These tasks could only be solved by airborne patrols during fire-danger periods. Observations in the thermal range are the most important for the early detection and monitoring of fire centers. For example, the IR-scanning system "Vulkan" was tested on board IL-14 and An-30 aircraft (Valendik and Sukhinin, 1991). The observation of fires in two channels (spectral bands 3–5 μm and 8–14 μm) provides a clear contour of the fire. These contours are usually difficult to obtain in other cases, because of large temperature differences between the fire center and surrounding areas. The method of matching the two images (8–14 μm, tuned for background, and 3-5 μm, tuned for high temperature objects) allows the borders of the fire to be determined. Such testing was carried out by the SBRAS Forest Institute during the development of the "Prognosis" System. The IR-technique for the detection of fire areas is typically combined with observations in the microwave spectrum. Shuttle flights of aircrafts with IR and radar equipment above fire areas allows the detection and monitoring of forest fire areas, which are usually covered by deep smoke and cloudiness, during a single flight.

Detection and observation of areas passed by fires began with the first remote images available for civil departments. The first experimental investigations were based on spectrazonal space photo images with a resolution of 15–20 meters. These experiments resulted in practical implementations: recommendations on the detection and mapping of recently burned areas based on satellite images (1979); and technical instructions on how to detect current changes in forest reserve areas caused by human activities and natural calamities (1982). During the 1980s, about 600 million hectares in Siberia and the Far

East were surveyed by these methods (Gusev and Sinitsyn, 1981; Isaev, 1995; Gusev, 1998).

Modern technology for large fire detection and estimation of their consequences has been widely implemented. The technology is based on images from MSU-SK and MSU-S scanners and automatic processing (Breido *et al.*, 1995; Breido *et al*., 1992). The processing of information in raster (images) and vector (maps) form is carried out in a GIS environment. The problem of detection of forest fire centers has been solved in an interesting way. The fire center is recognized by the smoke trace in the visible band (0.5–0.7 μm). In the near IR spectral range most of the traces are transparent and invisible on the image, but polygons of burned areas have the highest contrast in the near IR range (0.8–1.1 μm). Thus, coordinates of the fire center are registered at the first stage, and then one can observe the spread of the fire and estimate the area that is burning.

Automated technology for observation of large forest fires have the following stages:

1. Development or purchase of a digital topographic base with the boundaries of forest enterprises.
2. Creation of a database with coordinates of forest fire centers. Geographical coordinates can be obtained through links with the Space Information Receiving Centers, Forest Air Protection Service, and/or by interpretation of scanner images of fire centers.
3. Acquisition of satellite scanner IR images for the territory with registered coordinates of fire centers; analysis of space images; selection of burned areas; determination of boundary coordinates; geometric correction of contours; removal of distortions caused by non-linearity of the MSU-S and MSU-SK scanning devices; assignment of the scanner images to a digital topographic base with the bearing points; registration of the scanner images into the cartographical database.
4. In order to increase the accuracy of statistical accounts for a specific forest enterprise, boundaries of burned areas are marked on 1:1000000 scale maps. For federal or regional levels, 1:8000000 scale maps are used.

This technology was evaluated during the observation of more than 1500 large burns. Recognition, contouring, and mapping of one object takes about 3–4 minutes. Errors in the determination of burned areas greater than 200 hectares are 10–15%. The total burned area observed during the experiment in 1990 was 350,000 hectares (Breido *et al*., 1995).

From a practical point of view, it is not enough to determine centers of forest fires and to estimate burned areas. It is also necessary to estimate the damage and to evaluate the loss. Until recently, detailed investigations of post fire areas were made by assessments from aircraft. This air assessment is currently being replaced by an operational aerial video observation. It is a more efficient and cheaper method for operational detection and monitoring. The observations are made by a video camera on an aircraft or helicopter both in nadir and lateral directions. Expert evaluation of video observations of burned territories in the Lake Baikal water-conservation area and in the Sahalin territory showed that video images can provide reliable information on the type of fire, the intensity of the fire and the species composition of damaged forests (Breido *et al.*, 1992). Video information improves the reliability of aerial observations because the analysis of images can be continued or replayed in office conditions. The advantage of video observation is that by changing the focal length one can get and combine images of different scales when flying at the same height. For example, one can make observations with minimal and maximal focal lengths in order to estimate total damage of forests in the investigated territory, and to analyze the state of single trees on large-scale still photographs. For lateral video observation it is also relevant to use images with different scales. Relatively small scale lateral video observations provide visual estimates of the size and configuration of burned areas and identification of areas requiring detailed observations. Tree crowns, especially coniferous tree crowns, are clearly visible on detailed large scale lateral images, which makes it possible to determine the degree of damage (Breido *et al.*, 1992). Methods for video monitoring and analysis of video images are currently further developed in the Department of Remote Sensing Methods of the *VNIICLesresurs*.

The International Forestry Institute, together with the RAS Institute of Space Research, has developed Forest Fire Information System at the federal level. The GIS component of the system is based on the Internet. The system is used by the Forest Air Protection Central Base. The system provides background information on forest fire protection using digitized maps, traditional data and methods of forest fire protection, meteorological data, cloudiness, and information on current forest fires from satellite NOAA (Bartalev, 1998).

The existing forest fire monitoring GIS, based on on-ground, aircraft and satellite (NOAA) information, allows the identification and mapping of large fires. The system can be modified by medium resolution satellite images. It will allow estimation of the level of damage to stands affected by fire, estimation of consumption of forest fuel and post fire die-back (mortality) and, consequently, estimation of the impact of direct emissions and post-fire destruction on the forest carbon budget. The Forest Fire GIS has been developed in the Komi Republic in 1998 with a basic scale of 1:1000000, and is connected with remotely sensed data. The information base of the GIS is (1) the GIS layer “Block” *(kvartal)* forest inventory, which contains forest information on blocks which are compatible with the resolution of available satellite data, and (2) the forest fire databank for the territories of the Republic (Polshvedkin *et al.*, 1998).

8.2 Harvest and Reforestation

Sustainable industrial use of forest assumes harvest of mature stands. Strict limits on the amount of wood harvested and the location of harvest areas, as well as prompt reforestation of harvested areas by economically valuable species, are required by the forest management manuals. Nevertheless, sustainable forest management principles are often violated. This results in local and regional overharvesting. High productivity stands with commercially valuable tree species are often harvested while low productivity deciduous stands are left. The location and size of harvested areas often violate the harvest rules. Significant amounts of wood are left on the ground after harvesting, and undergrowth of valuable species are damaged. There are many years of experiences on the implementation of spectrazonal space images for accounting of the changes in the forest reserve area due to harvesting. These images allow the determination of areas actually harvested and the identification of violations of harvest rules with acceptable accuracy. This approach has been used for harvest control in forest industry enterprises as well as for forest harvest inspection in forests transferred to long-term leases (Danjulis and Zhirin, 1989). The most recent application of this method is the automatic estimation of the forest harvest (Breido *et al*., 1992; Breido *et al*., 1995). Space information is used for detection of violations of the harvest rules. Such violations include illegal harvesting methods (e.g., clearcutting instead of selective harvesting), exceedence of allowed sizes, exceeding allowable harvest area borders, etc. The cleanup of clearcut areas and preservation of the undergrowth and soil cover can be monitored using large-scale black-and-white aerial photography. In order to detect violations of the rules with space images, it is necessary to know the spatial characteristics of the harvested areas and the taxation indicators of harvested forests. Therefore, data from the forest inventory, cartographic materials, etc., are used as well.

Interpretation of harvested areas is conducted by visual or an automatic methods using 1:270000 scale spectrazonal space photo images from "Resource-F" satellites with a resolution of 5–10 m contact, or by using increased scales from 1:50000 to 1:70000. In space images of such scales harvested areas can be recognized by specific features of the borders (harvested areas typically have geometrically precise borders) and image tone and color, with a probability of 0.85 or greater for a minimum area of 2–3 hectares (Zhirin, 1998a).

The control of harvested areas requires the determination of the following parameters in images: width, length and area of harvested territory; identification of contiguous strips; and direction of logging. The following values of mean square deviations are permitted: ±10–12% for width and length, and ±15–17% for the harvested area. Deviation of the direction of logging is considered as a violation if the longer side of the harvested area deviates by more than 30° from a given direction. The direction of harvest is determined by comparison of old and new harvested areas in space images taken at different times. Type and intervals of the contiguity of harvested areas is determined by comparison of images of different times, forest plans and maps, data from the forest inventory, etc. Comparative experiments have shown that it is possible to use different sensors. For instance, the application of 1:127000 scale spectral photographs acquired by the KFA-1000 (resolution 7–8 m) and multiband images acquired using the SPOT HVR (resolution 10m) in taiga forests of the Irkutsk oblast showed that space images could be used to determinate the boundaries of clearcut areas with sufficient accuracy (Breido and Sukhikh, 1996). Spectrazonal space photography allows precise identification of insufficiently regenerated clearcut areas (accuracy 0.83) and where deciduous forests encroach on coniferous areas (0.84) (Sukhikh, 1996).

Automatic monitoring and estimation of harvests based on space images assumes (Breido and Sukhikh, 1995):

- digitization of images by an interactive processing system;
- interpretation of images with respect to delineation of harvest areas for a given year by comparisons with digital plans and maps;
- transformation of the contours of harvested areas to map projections and creation of a mapping data base;
- detection of violations of the harvest rules and deviations from harvest areas allotments;
- calculation of changes of areas and updating of mapping and inventory data bases;
- formation of mapping documents and inventory descriptions.

The digital mapping database is created using 1:25000 scale topographic and forest inventory maps. Experimental tests of the method have been conducted on the territory of forest enterprises in East Siberia.

Monitoring of reforestation on harvested areas is important as a source for forest management measures to support natural regeneration of forests with valuable species. Remotely sensed information is used for estimation of reforestation and formation of young stands where clear cuts were carried out on a large scale over a long period of time (Zhirin and Orlova, 1985).

The main stages of this approach are:

- visual interpretation of recent and non-regenerated harvested areas, with sufficient regeneration of either coniferous or deciduous species and areas with mixed regeneration, in contact or increased spectrazonal 1:270000 scale space photo images from “Resource-F” satellites with a spatial resolution of 5–10 m. The stratification of harvested areas is based on landscape regularities and takes into account similarity of regeneration processes;
- application of large scale samples from aerial photographs within harvested areas. The number of sample images is calculated by strata. The aerial photography is provided at scales of 1:1000 to 1:1500 on spectrazonal film during early spring;
- interpretation of large scale photos in order to estimate number and distribution by area of successful coniferous undergrowth; and
- development of maps at the scale of 1:50 000 on which density, spatial distribution and quality of undergrowth are indicated.

This approach was evaluated in practice in the taiga regions of the European North and has been adapted to the specific forest growth conditions of water-conservation zones of the Lake Baikal region (Orlova and Vukolova, 1997).

Since 1982, assessments of the violations of the harvest rules — including the volume of harvested unremoved wood, non-harvested areas within harvest allotments, and areas with destroyed undergrowth — is carried out by the help of large scale aerial photographs. The approach for the survey includes:

- detailed estimation of the conditions of harvested areas by using black-and-white aerial photographs at the scale of 1:1300 to 1:2000; and
- control of the correspondence of the harvested areas with the permitted areas as well as the identification of non-harvested areas within harvest allotments is carried out by using images at the scale from 1:6000 to 1:9000 (Tjurin, 1991).

Improvement of the estimation of reforestation on harvested areas as well as the survey of harvested areas are possible by replacing large scale aerial photography by nadir video observation. Experimental video observations in the Moscow region and in the European Russian North support an application of video observation for interpretation of boundaries and conditions in harvested areas. Exploitable and non-exploitable parts of harvested areas, seed trees, areas with sufficient undergrowth, and unlogged areas are identified by video observation. Large scale images (observation with a maximum focal length) are suitable for the assessment of undergrowth and estimation of the volume of wood left behind on harvested areas (Vukolova and Orlova, 1997),

8.3 Insects, Forest Diseases, Influence of Industrial Pollution

Biotic and anthropogenic factors may cause physiological and morphological changes in individual trees. The manuals and instructions of the Federal Forest Service require the classification of forests into 6 categories based on visual evaluation of physiological and morphological signs:

I healthy;
II weakened;
II strongly weakened;
IV dying;
V standing, recently dead trees;
VI standing, long-dead trees.

Physiological and morphological changes that accompany the health decline of trees are visible through the color of the needles and the leaf and the structure of the crown. Assessments of such changes are conducted by both ground based and aerial-visual special forest pathology surveys (*lesopatologicheskoe obsledovanie)*.

Spectral investigations have showed that the observation should be provided in narrow spectral intervals, including the IR band, in order to assess the state of a tree. By comparing the spectral coefficients of the brightness of the needles and leaves of trees, long-term industrial pollution can be detected. The key parameters include:

- the reflectance of damaged needles and leaves is higher in the spectral zone of chlorophyll absorption (0.65–0.76 μm) in comparison with healthy trees; and
- the reflectance of damaged needles and leaves is significantly lower in the near IR (0.76–1.1μm) zone.

In order to monitor damage to trees and stands, aerial photography is conducted using either the two-layer CN-6M and CN-8 or the three-layer CN-15 spectrazonal films or using multizonal observation.

The assessment of information content of spectrazonal aerial photographs at scale from 1:5000 to 1:10000 has shown their capability to identify two groups of trees: healthy (tree state categories I–III) and dead trees (categories IV–VI). The probability of the accurate determination is 0.87 for the I–III categories, and 0.84 for the IV–VI categories (Zhirin, 1998a). Image color is the main indication of dying and dead trees.

Super large-scale (1:350–1:830) spectrazonal aerial photographs have been investigated in order to assess early stages of damage for pine, cedar, and birch. Interpretation of images by stereo devices can detect the main features of weakened and strongly weakened trees, namely, the amount of dry twigs in crowns, pathologies in the shape of the crown, and the density and compactness of crowns (Danjulis and Zhirin, 1989). 1:350 scale images yield the best information content on crown structure. Decreasing the scale causes generalization and loss of detail in crown images. Under these decreased scales, color signals are much more informative. Based on experimental studies, aerial images at scales of 1:800 to 1:900 are best for assessment of the pathology of individual trees. Aerial images with scales ranging from 1:1000 to 1:3000 are recommended for assessment of the level of damage to forest stands, by determining the relative number of trees in different health conditions (Danjulis and Zhirin, 1989).

Several conclusions were drawn after experiments on the assessment of coniferous stands damaged by industrial pollution in the Lake Baikal watershed area. Spectrazonal aerial photographic images of the scale of 1:5000 to 1:10000 produced on three-layer films are suitable for assessing the degree of stand damage by both visual and automatic methods. The accuracy of such interpretation is about 8–10% for visual and 12–15% for automatic interpretation (Malysheva, 1996).

Implementation of aerial photographs for forest pathology surveys makes it possible to decrease the volume of on-ground measurements. However, it cannot replace on-ground measurement completely. Many details of forest damage cannot be identified with any remote sensing method.

Space images have even greater limitations for determining the general health of forests. They are more suitable for analysis of spatial regularities in distribution of pests and diseases, their association with specific landscape features, and for territorial stratification (Isaev *et al.*, 1991; Malysheva and Sukhikh, 1991). However, catastrophic pest outbreaks are an exception. For example, the large scale infestation by *Denrolimus sibirica* in Krasnoyarsk Krai in 1994–1996 was reliably detected on scanner multizonal SPOT images. Interpretation of images, together with selected spectrazonal aerial photographs (in the scale of 1:20000 to 1:25000) and ground observations, made it possible to classify forests by their degree of damage. Processing of aerial photographs and space images from SPOT was conducted by using the software ERDAS Imagine 8.2 in this application (Project on Management of Environment…, 1997; Project on Studies of Characteristics…, 1998).

Space images are suitable for stratification of forests in zones with significant air pollution. This was demonstrated in forest surveys of the South Ural region, where the Karabashskii copper enterprise is located. Space scanner images allowed the identification of three ecological zones in forest ecosystems: impacted zones, buffer zones, and undisturbed zones. Analysis of images taken at different times from “Fragment” (1983) and MSU-E (1992) illustrated the possibility of monitoring the dynamics of borders between impacted and buffer zones as the forest recovers after a reduction of industrial pollution (Butusov *et al*., 1996; Butusov *et al*., 1998). However, the rough estimation of the forest ecological condition achievable with space images is not enough for adequate decision making. The stratification plays a role for the planning of more detailed surveys using aerial photographs and visual observations.

Aerial video observation is believed to have the potential to assess forest health. Results of several experiments made by VNIIZlesresurs confirm the usefulness of video images for detection and identification of weakened and dead trees and changes in the structure of forest cover damaged by insects, pests and industrial pollutants. The video system SILVACAM, developed by the Finnish firm Karelsilva, was tested in 1994 by the joint work of specialists from VNIICLesresurs, the US Forest Service, and the Finnish Forest Research Institute. The experiments were conducted in Finnish Lapland in the Pallas Ounas National Park, a forest area which has not been impacted by unfavorable factors, and in areas damaged by a complex of different factors (insects, pests, forest diseases, industrial pollutants). The application of optical nozzles provides video images with initial scales of 1:8000, 1:4000 and 1:2000. Observation by the video system SILVACAM was made in 3 spectral ranges (0.49–0.58, 0.58–0.68, and 0.76–0.9 μm) and with a spatial resolution of 500 lines per horizontal row. Due to the high resolution and observation of reflection in the near IR-zone, such images are similar to those obtainable from traditional spectrazonal aerial photographs. Video images obtained in the test were digitized, corrected, transformed, processed by ERDAS and MIPS software, and combined with maps of test areas in GIS-environment.

Video observation was successfully used in Krasnoyarsk Krai in 1996 in order to assess dark coniferous forests damaged by *Dendrolimus sibirica* in a project financed by the World Bank. Aerial video observation was made from the AN-2 aircraft in nadir and lateral directions. The alternation of observations with minimum and maximum focal lengths (duration 3–5 sec for each) made it possible to estimate the general damage of forests along the routes and to analyze the condition of separate trees on the larger scale images. The elimination of image blurring during the observation is the most difficult technical problem. A special video camera with increased recording speed (so-called stroboscopic effect) was used in the experiment. Such high frequency discrete recording provides clearness and sharpness for all image stills. These images could then be used for both visual and automatic processing.

The comparison of the results of video images and ground surveys showed that damage of canopy layers and separate trees can be classified according to following scales:

- point (individual trees are damaged);

- mosaic (small groups of trees are damaged);
- clump (large groups of trees are damaged);
- entire (the majority of trees are damaged).

Based on detailed large scale video images, three stages of canopy damage can be identified:

- healthy (crown damage is less than 25%);
- damaged (crown damage is from 25 to 75%);
- dead (crown damage is more than 75%).

The automatic image processing used the TOPOL software (Project on Management of Environment…, 1997).

Finally, other special forest surveys based on remotely sensed data include:

- remote sensing control of changes in forest reserve areas caused by oil exploration and extraction (Methodology for Remote Control …, 1990; Sedykh, 1996);
- agro-forest-meliorative assessment of protective forests in forest-steppe and desert zones (Zhirin, 1984; Zhirin, 1991); and
- monitoring of technical conditions of forest-drainage systems (Danjulis and Zhirin, 1989; Berezin, 1995).

Special forest surveys were developed independently for different years. These surveys created a scientific and methodological basis for assessments of forest ecosystem conditions (ecological potential) and forest resource utilization (forest potential) by forest monitoring.

9 Aerial and Space-Based Monitoring

The protected area of the Lake Baikal region was used as a test area for development of principles and practical implementation of a new system of regional forest monitoring. This system includes aerial and space-based observation combined with the storage and interpretation of the information, and makes extensive use of GIS-technologies (Malysheva, 1996).

The Lake Baikal watershed occupies more than 24 million hectares. Forest monitoring in the region requires maximal use of aerial and space methods. The multi-step principle for data collection includes identification of homogeneous landscape units (although not separate stands) in space images and estimation of the ecological stability of specified forest regions according to a set of generalized signals. Medium and large scale aerial photographs provide detailed quantitative and qualitative characteristics of forest stands and other forest land cover categories, such as harvested areas and burns.

The principle of selection is implemented by selecting potential ecologically unsatisfactory zones based on all available information. This information includes small scale space images, official statistics, mapping materials, and results from special studies. Based on the preliminary work, special surveys can be planned for forests that are damaged or are under the threat of damage by different factors.

The spatial organization of the data collection should be compatible with principles which have been used under the establishment of the monitoring system. The monitoring system is intended for multi-purpose use, although the primary uses are forest and water management. Therefore, collection and systematization of data was conducted for different territorial units:

- units of natural regionalization (hydrological regions) and natural units of observation (NUO), associated with different order watersheds; and
- administrative and management units (republic/*oblast*, forest enterprise, national park, and natural reserve).

Space and aerial observation allows the collection of data for characterizing the water-regulative and water conserving functions of forests, as well as the forest resource potential within the whole region. In order to assess the water protective functions of forests (and to characterize the dynamics of indicators for ecological sustainability of forests in river basins) the following indices were used:

- percentage of forest cover — the ratio between the forested area and total land area of a river basin or NUO, (%);
- integrity — the ratio between forested areas and forest land (%);
- the share of coniferous forests within forested areas;
- the share of immature, mature and over-mature forests in forested areas (%);
- share of low-stocked and sparse coniferous forests in forested areas (%).

All of these indices are calculated based on interpretation of space images. Used together, they make it possible to estimate the sustainability of the regional forest ecosystems, to detect zones of strained ecological conditions, and to plan special types of surveys for the strained zones. The determination of these indices was made based on an original “discrete” (rather than full contour) interpretation of spectrazonal 1:270000 scale images from “Resource-F” satellites.

In order to assess the condition of forests within strained ecological zones, detected by space images, special methodologies have been experimentally developed. These methodologies include:

- The collection of data on the state of forests within zones of industrial pollution was based on large scale aerial photographs. The method provides objective information on the state of coniferous stands in inaccessible mountain areas, and can assess the degree of dessication based on spectrazonal aerial photo images at the scales from 1:5000 to 1:10000.

- The assessment of forest regeneration in harvested areas is based on a combination of space information and sampling of aerial photography images. The method includes the interpretation of spectrazonal space images in order to classify harvested areas, followed by the identification of detailed characteristics of the forest regeneration process based on sampling from large-scale aerial photographs (at the scale of 1:1000 to 1:1500) or video observation (Orlova and Vukolova, 1997).
- Video monitoring was used for identification of forest lands damaged by fires; state of harvested areas, and sanitary condition in forests damaged by diseases and entomology pests.

The landscape ecology database thus developed can serve as the nucleus of the forest monitoring system. The database development is based on the following principals:

- Indicators for water protective functions of forests, as well as for the forest resource potential, are collected from remote information. These indicators provided initial information for further monitoring of the forest condition. One of the database sections contains climatic, hydrologic, and forest-ecological information for the hydrological regions of the Lake Baikal ecosystem.
- There is a special approach for the division of the territory into observational units, such as river basins. This approach can combine river basins of different orders or different hydrological regions in order to obtain integrated indicators, as well as to link actual data with characteristics for water and thermal balances.
- The annual updating of the data is based on periodic data measurements of the current changes in forest reserve areas. During the period between forest inventories, changes (such as recently burned areas, harvested areas, wind damaged areas, areas affected by pests and diseases, industrially polluted areas, areas damaged by droughts, floods, snow-slips, etc.) are reported by different sources (including forest enterprises) and are represented in the data base.
- Reassessment of forest stability indicators for the whole region is provided every 10 years based on space images. More frequent interpretation of space images is necessary for those river basins having critical indices, in order to provide the necessary continuity of observations.
- Data for the interpretation and reference characteristics in the database are tied with the cartographic products. Customers can get these data in the form of “hard copies” (schematic maps) or in the form of electronic maps. These maps illustrate the changes of indices within hydrological regions and the water-protected zone as a whole. Such representation allows the division of the territory into districts, based to the ecological conditions.
- The combination of information in the database with digital cartographic databases containing boundaries of natural-territorial observation units and boundaries of administrative or economic units makes it possible to recalculate the indicators for each forest enterprise.

The database management system CLARION was chosen for the database development and for the development of a user-friendly interface. The combination of CLARION with GIS modules (EPPL-7) provides an integration of spatial and thematic information, as well as the ability to visualize the data in electronic maps and hard copies.

Use of analytical tools available in ARC/INFO 7.0 has allowed the detection of strained ecological zones in the water-protected territory of Lake Baikal. The Remote Sensing Department of *VNIICLesresurs,* which developed the scientific-methodological basis for the forest monitoring system of the water-protected area of Lake Baikal, has further developed and adapted the monitoring to the needs of ecological monitoring of forests in Russian National Parks.

10 Remote Sensing Applications and the Development of a New Forest Inventory and Monitoring System (NFIMS) in Russia

10.1 Rationale

The former Soviet Union developed an impressive forest inventory system. The first complete inventory of all forests of the country, including what is now Russia, was conducted in 1961 on the entire forest reserve area (about 1.2 billion hectares). Three basic methods have been used in Russian forest inventory over the last few decades. These are *lesoustroistvo* or forest inventory and planning (FIP), *aerotaxation* (aerial inventory methods), and *remote sensing*. A concise description of these methods, including their abilities, details, accuracy, and application in Russia in 1960–1990s, are given in Shvidenko and Nilsson (1997). By 1998, the area inventoried by FIP amounted to 670.2 million hectares, or 60% of total forest reserve area. Most areas inventoried by FIP are managed forests. 268.2 million hectares (24%) were covered in the period 1978–1997 by satellite data. 172.1 million hectares (16%) of unused (apart from northern deer pastures) northern forests was inventoried by aerotaxation over forty years ago, and therefore cannot be used for forest management (Giryaev, 1998), as the data is obsolete and unreliable.

Since the middle of the 1990s, it has become evident that many countries, and particularly Russia, need a new system of forest inventory and monitoring (Strakhov *et al*., 1995, 2001; Giryaev, 1998; Varjo, 1997). All forest inventory activities and information flows should have a solid systems interconnection. This point of view was supported by the Russian Federal Forest Service when it approved a new concept of FIP (*lesoustroistvo*) (FFSR, 1993). The basic reasons in support of a new system are the (1) insufficient and obsolete technologies currently used in field measurements; (2) low quality of information; (3) lack of systems interaction between different types of forest inventory in Russia; (4) insufficient technical level of forest inventory, which has not significantly improved over the last few decades; and (5) the new social and economic situation in the country. Most of these shortcomings were inherent in the previous system, but were either unavoidable or not considered as crucial defects before the 1980s. New national and international requirements for forest information arising in the 1980s and early 1990s and during the transition period in Russia from 1991 to 1998 have resulted in new problems and needs. Briefly, the major current shortcomings of the existing system of forest inventory and monitoring (and therefore the problems to be addressed by any new system) in Russia are:

1. The existing information is incomplete and/or inaccurate. Most FIP information is a combination of visual estimates of biometric indicators of stands with a limited amount of direct measurements. The accuracy of these data are unknown. There is much evidence that this information contains systematic errors, particularly for growing stock (in the range of -6% to 20% for mature stands). This level of accuracy is not acceptable, particularly for forest management in a market economy. Examples of incomplete information include the lack of several important indicators of productivity and ecological functions of forests (Sedykh, 1999) and incomplete descriptions of wood quality in mature forests. One of the biggest gaps is the lack of estimates of general value of primary forest inventory units, including estimates of the resource, ecological and social functions of forests.
2. Forest information is currently organized according to administrative regions. Solid ecological conclusions, however, can only be drawn for territories defined by natural boundaries.
3. Aggregated data for large regions and the whole country, used as the basis of state forest policy, are a mixture of heterogeneous information generated by different methods and in different years. The accuracy of the information is unknown. The economic and social crises in Russia have resulted in a decrease in the annually inventoried forest areas. Areas of on-ground forest inventory have decreased twofold compared to 1991. The total area inventoried was 33.4 million hectares in 1997, whereas the areas requiring inventory were about 60 million hectares. In addition, FIP data is gradually becoming obsolete. Of 670 million hectares of managed forests in 1997, 72% had been inventoried during the previous decade, 19% from 11 to 15 years before, 7% from 16 to 20 years before, and 2% had not been inventoried in the previous 20 years (Giryaev, 1998).
4. The technical basis of inventory methods, and use of this information for forest management, is inadequate. The Russian Federal Forest Service officially approved “The program of informatization of forest management in Russia” on 23 February 1998, and “The program of implementation of GIS technology in forest inventory and planning” on 20 May 1998. The latter suggests that GIS-technologies in 88 administrative divisions of the Russian Federation (on the regional level) be implemented, and that these technologies be developed and used operationally in 1427 forest enterprises. These documents are important for the strategic development of future forest inventory and forestry in Russia. However, they currently have only a modest impact, as most forest enterprises still rely on paper technologies rather than computer-based systems.

5. Russian forests require the use of a comprehensive system of remote sensing applications. However, remote sensing applications in Russian forestry has been characterized as being in a deep crisis (Sukhikh, 1998; Filippchuk, 1998).
6. The Fourth All-Russia Congress of Foresters approved "The Concept of Sustainable Forest Management in Russia" in 1998. The Federal Forest Service approved the "Criteria and indicators of sustainable forest management" in February 1998. The indicators included in this document have been selected exclusively from those identified by the existing forest inventory, and are therefore incomplete. Nevertheless, these documents define a crucial prerequisite for the development of a new system of forest inventory in Russia — namely, that the system should supply the information necessary to implement sustainable forest management.
7. Two consequences follow from the previous item. With respect to the criteria and indicators of sustainable forest management, the environmental role of forests should be estimated not only for forest territories, but as a stabilized element for all land-use/land-cover classes of natural landscapes. This means that both new sources of information and information output should be developed in order to satisfy these requirements. A comprehensive landscape description is needed as an input. A theory (which should provide indicators) of the environmental quality of landscapes should be developed as the output. Second, the efficient implementation of sustainable forest management should have a system of certification of forest products as its practical output. The NFIMS should yield sufficient and timely information to solve this task.

10.2 Details of the New Forest Inventory and Monitoring System

In order to satisfy the information needs of sustainable forest management, three major interconnected goals should be adopted, similar to those introduced in the Forest Assessment and Monitoring Environment (FAME) by de Gier *et al*. (1999).

1. The provision of aggregated information on forest resources to federal and regional state and forest management bodies. This information will form the basis of national forest policy development, as well as the basis for the establishment of middle- and long-term programs for forest management.
2. The creation of a reliable and relevant monitoring system for estimating the condition and dynamic of forests.
3. The provision of practical information for forest management operations.

These three goals to some extent associate with three spatial level of forest management (federal, regional, local) and correspond to three major structural parts of the NFIMS for Russia (*Figure 1*): national inventory, monitoring, and FIP (*lesoustroistvo*).

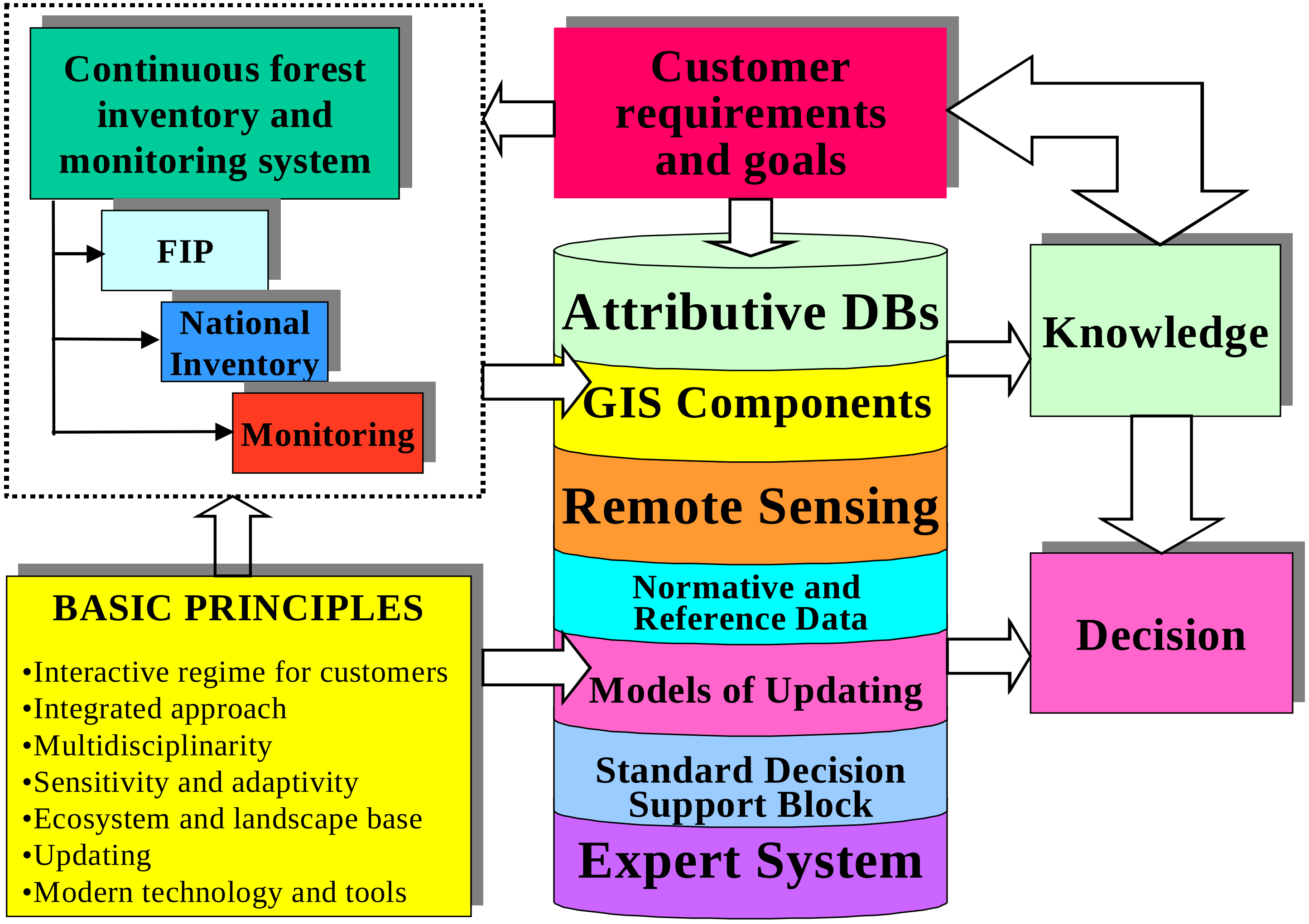

Figure 1: Conceptual Structure of the New Forest Inventory and Monitoring System for Russia (Project).

10.2.1 National inventory

The national inventory subsystem should provide reliable information on forests for Russia as a whole, as well as for major regions. The nucleus of the national inventory is an internally consistent set of data from the State Forest Account, sampling measurements, comprehensive descriptions of landscapes, remote sensing applications, and modeling. This is a complicated problem in a country as large and distinctive as Russia. Solving it by traditional methods (for example, such as those applied in Nordic countries) is not likely to be appropriate. The primary requirements are an appropriate regionalization of Russian territories for the national inventory, a significant increase in the use of remote sensing, the use of recent developments in mathematical and statistical forest inventory methods, and the improvement of all other types of forest inventory technologies.

10.2.2 Monitoring

The monitoring subsystem should include programs for (a) monitoring of the state of forest reserve lands and other forest resources; (b) forest pathology monitoring; (c) fire protection monitoring; (d) special types of monitoring, e.g., monitoring of industrial and radioactive contamination; and (e) monitoring of forest carbon budget for accounting and management purposes.

Monitoring of state of lands of forest reserve lands and forest resources, which is currently based on the data of State Forest Account and on official statistics, is considered as one of major goals of the national inventory. Forest pathology monitoring is a major element in controlling the health of forests. This includes monitoring of their stability, the population dynamics of dangerous insects, the distribution of diseases, and other anthropogenic factors which result in the weakening and death of forests. Although there is much evidence of the effectiveness of such applications (Isaev, 1997), the current use of remote sensing for this type of monitoring is insufficient. Forest fire protection monitoring is a part of the information supplied by the forest fire protection system and provides forecasts of forest fire threat, identification of forest fires, and estimates of their consequences. This type of monitoring is provided by state forest management bodies, air forest fire protection central bases *(Avialesookhrana)* and *VNIIZlesresurs*. Special types of monitoring provide information on the distribution and impact of radioactive, industrial and other types of anthropogenic pollution on forest land, forests, and forest products. The need for a special subsystem for monitoring the forest carbon budget is the result of the post-Kyoto negotiation process.

All of these monitoring programs should be present in the NFIMS. The programs require (1) a significant increase in the internal consistency of data, (2) a significant improvement in remote sensing applications, (3) the use of new indicators (e.g., for quantification of forests stability) and new technologies for their identification, and (4) the use of a geographic information system as the basis for integrating all available information.

*10.2.3 Forest inventory and planning (*lesoustroistvo*)*

Urgent transition to a continuous forest inventory and planning (CFIP) program is considered as a very important, if not the most important, development of the existing system of forest inventory for managed forests. The CFIP consists of a basic inventory, with a further permanent inventory of the primary units of forest inventory (PUFI) which have been affected by forest management or natural disturbances. A special program is necessary for updating data for other areas (i.e., those that were not impacted). The basic inventory should be conducted by the most accurate methods, with simultaneous development of corresponding components of GIS and associated attribute databases. Russia has many years of experience in implementing the CFIP for selected forest enterprises, but it has not led to significant improvements in the quality of information and/or to changes in the ideology of forest management. The necessary preconditions for wide implementation of the CFIP are:

- the improvement of methods and technologies for collecting and processing forest taxation data, intended to provide a transition to a systems application of measuring methods of inventory;
- the availability of comprehensive landscape descriptions in the form of multi-layer GIS and associated attribute databases;
- strict regulations defining the duties of forest inventory enterprises and forest management enterprises participating in the CFIP;
- the development of an automated forest reserve data bank (based on the PUFI as the smallest information element) with a corresponding GIS, appropriate software, and the availability of equipment and qualified professionals;
- CFIP must be implemented in forest management activities in which more than 1.5% of the primary inventory units undergo changes in their characteristics (land cover category, species composition, age, growing stock, etc.);
- arrangement for a long period of cooperation between the forest enterprises and the regional forest inventory enterprises; and
- availability of reliable guidance on the most up-to-date normative and reference documents. A system for updating for the attribute database is particularly necessary.

The NFIMS should include (Giryaev, 1998; Strakhov *et al*., 2001):

- advanced technologies for remote sensing of forest lands based on a variety of satellites, aircraft, and sensors, including non-secret information gathered by national security satellite systems (e.g., those of the Ministry of Defence);
- appropriate methods, techniques and norms for forest monitoring;

- improved methods and technologies for photo-statistical forest inventory based on multi-spectral scanning;
- strong system interactions between information sources and the different structural elements of the NFIMS, in both attribute database and geographical information systems (GIS); and
- improvement of existing (and generation of new) regional and local standard methods using forest models and reference data for forest inventory, including models for stand growth and productivity.

Practical implementation of the system should provide for the creation of (1) a State Forest Cadastre which will contain information on the resource, ecological, economic and social value of forests; (2) a Permanent State Forest Account based on multiple sources, including the national inventory; (3) a sound background for operational forest management using the coupled ecosystem-landscape approach; and (4) relevant information for detailed analysis of forest reserve lots subject to market interactions.

We do not consider technical aspects of the NFIMS in great detail here. Nevertheless, we point out that serious problems in further development and implementation of the CFIP could result from inconsistent computer systems and software used by different regional Forest Inventory and Planning Enterprises (FIPEs). Currently, basic software for forest attribute databases varies between regions. For example, the West Siberian FIPE in Novosibirsk uses MAP/INFO, the Northern FIPE in Vologda uses GEOGRAF/GEODRAW, and the North Western FIPE in St. Petersburg uses WINGIS. The automated computer system ACS “LUGIS” is used by the North Western, South Eastern, Pribaikalskoe and Karelia FIPEs and seven administrative regions of the Russian Federation (Treifeld, 1998). Standardization is a prerequisite for further development of the NFIMS.

10.3 Remote Sensing in the NFIMS

As we mentioned above, the current state of remote sensing applications in Russia is in a deep decline. Inventory and mapping of reserved forests decreased from 22 to 13 million $ha \cdot yr^{-1}$ in 1998. Areas where aircraft are used to monitor harvested areas (which are very important for the taiga zone) decreased from 168 to 51 thousand hectares. Other types of inventory based on air and satellite methods are not being used, and new technologies are also not being used (Shubin, 1998). Nevertheless, it is evident that any new system will be not efficient without a complete and systematic application of remote sensing. The generation of new technical, scientific and methodological tools based on all of the existing sensors and the development of new remote sensing and computer techniques should correspond to current national and international needs and economic realities (Giryaev, 1998).

10.3.1 User requirements

The most complete analysis of user requirements for remote sensing information for sustainable management of forests has been recently done by the International Institute for Aerospace Survey and Earth Science (ITC) (de Gier *et al*., 1999, and associated technical papers). We use some of the results and recommendations of this study below. Nevertheless, specific characteristics of Russian forests and the economic and social circumstances of the country should be taken into account.

Major users of remote sensing in Russian forestry, classified by the scale of the data needed, include:

- Local level (scales from 1:1000 to 1:50000): managers and professionals of forest enterprises, Nature Protection Committees of the administrative districts, etc.
- Regional level (scales from 1:50000 to 1:1000000): regional bodies of Federal Forest Service, regional forest inventory and planning enterprises, regional offices of *Avialesookhrana*, regional Nature Protection Committees, regional governments, and NGOs.
- Federal level (scales from 1:1000000 to 1:10000000): the Federal Forest Service of Russia, other federal ministries (Ministry on Extraordinary Situations, State Nature Protection Committee, etc.), *Avialesookhrana*, universities, and NGOs.
- Continental and global level (scales above 1:2500000–1:5000000, but local to regional scale requirements could arise at the individual project level): international organizations and long-term scientific programs (such as UNEP, FAO, IPCC, IGBP, Global Observing Systems), global and continental environmental studies, different companies, national and international financial institutions (e.g., in the framework of the post-Kyoto negotiation process), etc.

User requirements and priorities could be significantly different for different levels and groups of users. There are many different constraints, including political, institutional, social, and technical requirements. In *Table 10* we present our view of the major constraints on remote sensing applications in the Russian forest sector. As can be seen from *Table 10*, most of the crucial constraints are outside of the forest sector. These constraints arise from the general political, social and economic situation in the country (cf. Nilsson and Shvidenko, 1998).

Table 10: Main constraints of remote sensing applications in the forest sector in Russia (modified from de Gier *et al*., 1999).

Constraints	Nature and strictness of constraints				Level	
	Polit-ical	Institu-tional	Tech-nical	Human capacity	National	Regional
Inadequate formulation of policies	2				2	2
Inadequate implementations of policies	3	3			3	3
Lack of political will	3				3	3
Over-sensitiveness regarding national security	3				3	2
Insufficient implementation of sustainable forest management	3				3	3
Inadequate organizational structure	2	3			2	3
Inadequate organizational capacity	2	3			3	3
Inadequate information strategy	2	2	3	1	3	3
Lack of appropriate information systems	2	3	3	2	3	3
Over-centralized control of flow of information	3	3			3	1
Lack of standardization/compatibility	3		3		3	2
Inadequate human capacity/training	2	3	2	2	1	3
Poor working/technical conditions	3	2	3	1	3	3
Inadequate communication between levels	2	3	3	3	3	2
Inadequate methods and systems	1	2	3	3	3	2
Inappropriate technology/insufficient techniques	2	2	3	2	2	2
Inadequate user friendliness			2	2	2	2
Insufficient inter-disciplinarity	3	3	3	3	3	2
Shortage of accurate field data		2	3	1	3	2
Usability (inadequate data)		2	3	3	3	3
Unavailability of data, specifically from western satellite system	2	3	3	2	2	3
Lack of affordability of data (cost constraints)	3	3			3	3
Timeliness (delay in procurement/delivery)		2	3		2	2
Lack of interests in reliable/operative data	2	2			1	2

Note: estimates of expert ranking of the importance of specific constraints are given by figures:

1 — constraint is significant but can be overcome by efforts within the forest sector (e.g., by the Federal Forest Service);

2 — constraint is of major importance. The solution requires political, institutional, and economic efforts at national/regional levels;

3 — constraint is crucial for implementation of the system. These constraints require fundamental political and economic decisions.

10.3.2 Capabilities of remote sensing based systems

In this report, we have estimated the capabilities of remote sensing tools available in Russia. For general estimates of modern Western remote sensing systems and key system requirements for land and forest assessment, we refer to the extended analysis in de Gier *et al*. (1999). A short technical description of the most appropriate current and prospective remote sensing systems (including Russian sensors and equipment) applicable for the forest inventory and monitoring system in Russia is presented in Appendix 3. Expert estimates of application possibilities are given in *Table 11*.

Table 11: Application possibilities of remote sensing systems

Subsystems of FIMS	Aerial photo	Satellite photo	Satellite scanning	Airborne radar	Satellite radar	Airborne laser	Airborne video
National inventory of managed forests	2	1	1	3	2	3	3
National inventory of reserved forests	3	1	1	3	2	3	4
CFIP (intensive forest monitoring)	1	3	3	4	4	4	1
CFIP (moderate forest monitoring)	1	2	2	3	3	3	2
Land-use monitoring	2	2	2	2	2	4	2
Forest fire monitoring	2	1	1	2	2	3	2
Forest pathology monitoring	1	2	2	3	3	4	2
Control of forest management	1	2	2	2	3	4	1
Special monitoring	2	2	2	2	2	2	2
Carbon management	1	1	1	3	2	3	2

1 — widely applicable.
2 — moderately applicable.
3 — limited applications (auxiliary technical application).
4 — usually inapplicable.

10.3.3 Special issue — monitoring of the carbon budget

Russia has signed the Kyoto Protocol to the UN Framework Convention on Climate Change. It must therefore develop a national system of greenhouse gas emission monitoring, including the impact of terrestrial biota (which, in Russia, are essentially forests) on the carbon budget. The international community has not yet reached a consensus on how to implement the Kyoto Protocol. One of the relevant approaches is that “Kyoto forests”, as a partial account for carbon, should be monitored in a system with strong interconnections with the full forest carbon account for the country. Thus, the NFIMS should include a program for monitoring the carbon budget of Russian forests. “A full carbon budget encompasses all components of all ecosystems and is applied continuously in time” (Steffen *et al.*, 1998). This means that any carbon accounting program requires information from almost all of the FIMS information sources. Those information sources should therefore specifically address information needs for carbon accounting. IIASA's experience in the development of the full carbon budget of Russian forests (Nilsson *et al.*, 2000) has led to the conclusion that the most important carbon budget uncertainties are related to:

- estimation of current productivity of forests expressed in terms of gross growth, net growth, mortality and net primary production;
- monitoring of disturbances (forest fires, outbreaks of insects and diseases, harvesting, industrial transformation, and pollution), including their distribution, severity, rate of ecosystem transformation, and post disturbance impact;
- evaluation of the dynamics of organic matter from dead vegetation in forest ecosystems (detritus, litter);
- evaluation of the dynamics of soil organic matter; and
- evaluation of restoration processes in forest ecosystems, particularly natural regeneration of forests after fires or harvests.

The processes listed above show the relevance of using multisensor and multilayer remote sensing based systems in combination with on-ground measurements. As a general outline of such a system, a four-layer system could be used:

1. low resolution satellite data for the identification of major land-use/land-cover classes, aggregated estimates of productivity, and identification of large fires (only for the relatively homogenous remote northern territories);
2. medium resolution satellite data for increasing the accuracy of land cover classification and disturbances;
3. high resolution satellite and airborne data for monitoring territories where significant change is occuring, such as zones of intensive forest management; and
4. on-ground measurements. The coarse layers of the system are designed for identification of areas in which rapid transformation of land cover classes is taking place (or is expected to take place), followed up by detailed observations in selected regions.

There will be an increasing use of models which use parameters directly calculated from remote sensing measurements. Such parameters include leaf area index (LAI), photosynthetic active radiation (PAR), fraction of incident photosynthetic radiation absorbed by green leaves in the forest canopy (FPAR), above-ground phytomass and NPP. A variety of methods (e.g., model inversion, look-up tables, vegetation-index based) and sensors (e.g., MODIS, AVHRR, VEGETATION, MISR, MERIS, POLDER) could be used (Goetz and Prince, 1996; Ahern *et al*., 1998).

Two tools will play a particular role in monitoring of the carbon budget. First, availability of an integrated land information system is a crucial prerequisite for carbon accounting. This will serve as a basis for reliable scaling-up of direct observations of spatial ecosystem dynamics to regional levels. Second, different types of modeling are required for the subsystem. For example, due to the strong correlation between types of forest stands, soil types, amount of detritus, etc., and ecosystem function processes, regression models (as well as other types of models) for indirect estimation of variables based on remotely sensed data may be used. Even more important is the development of fundamentally new regional models of vegetation dynamics and carbon budget accounting. The input parameters of these models would include a comprehensive description of landscapes at relevant scales (i.e., the Land Information System should be implemented), semi-empirical models of succession dynamics and productivity of vegetation, physiological models (in order to take into account diversity and dynamics of environmental variables), and transformation matrices of remotely measured indicators.

10.3.4 Collaboration and links with international systems and long-term projects

The global scale of the Russian forests results in a solid basis for links and collaboration with international observation and information system and long-term projects. We give only three examples. The International Global Observation Strategy (IGOS) unifies the major satellite and surface based systems for global environmental observation of the atmosphere, oceans, and land. It includes GTOS (Global Terrestrial Observing System), GCOS (Global Climate Observing System) and GOOS (Global Ocean Observing System). Based on the recognition that data collection must be user driven, the major goals of IGOS are to facilitate strategic planning and to provide a coherent and comprehensive approach to environmental observations, covering all forms of data collection.

The other example is the Global Observation of Forest Cover (GOFC), an ambitious Canadian pilot project with the goal of producing high quality, multi-resolution, multi-temporal datasets of forest cover and attributes, and products derived from these datasets, with particular attention to areas of rapid change and fragmentation. Regional applications and methodological investigations, as well as an ultimate transition to routine operational use, are among the fundamental goals of this project.

Baseline user requirements for fine resolution GOFC products have much in common with national and regional level needs. Three uses are considered. Classification and inventory of forests include: classification of forests by leaf morphology and physiognomy; by dominant species; by % of closure (5 classes are suggested); by age groups (at least 3 classes); and biomass per forest type identification. Forest change includes fire (area and number of fires; fire intensity; residuals after burning), harvest (area and type of harvest), insect and disease (area and severity) and regeneration (areas regrowing and rates of regrowth). The problem of reforestation, afforestation, and deforestation requires knowledge of the area and annual rate of deforestation; the area, extent and age of regrowth; the estimation of carbon stocks in forest and regrowth; and the level of fragmentation (i.e., spatial pattern of deforestation, regrowth, and fragments (Skole *et al*., 1998). The list of recommended sensors to support fine resolution GOFC product includes optical Landsat MSS, Landsat TM, SPOT XS, Spot Pan, IRS LISS, I,II, III, MOS MESSER, JERS-1/2 OPS, Landsat 7, and future SPOT 5, ASTER, AVNIR, LISS/IRS, ALOS AVNIR-2, ALOS PRISM. A significant amount of microwave sensors are also recommended (JERS-1, SIR-C, ERS-1/2, Radarsat, etc.).

The third example is the FIRS (Forest Information from Remote Sensing) — a project supported by the EU and focused on the development of a unified European forest information and communication system. The Project has recently (1994–1998) carried out a number of activities (applications of remote sensing to changes of forest lands, forest monitoring in Europe with remote sensing, evaluation of remotely sensed data for classifying and mapping the forests for the purpose of updating and contributing to a national forest inventory, etc., (Kennedy and Folving, 1997)), the results of which could be used in the development of the NFIMS.

11 Conclusions

Analysis of scientific literature and methodological documents produced during the last ten years (Methodology for Small-scale…, 1981; Technical Training of Specialists…, 1995; Appendix 1; other references in the text) shows that the theoretical basis of remote sensing applications in forest inventory and forest science is firmly established. Remote sensing has been used in different applications in Russia. Research has promoted the implementation of new methods and technologies for mapping, forest inventory, and for the assessment of forest conditions and dynamics. The current developmental trend is a systems approach, combining different methods in a unified system for collection, processing, analysis and dissemination of the information to users (cf. Appendix 4).

In conclusion, the application of remote sensing methods is a necessary part of any prospective system of forest inventory and monitoring in Russia. The development of the latter is an inevitable precondition of the transition of the Russian forest sector to the sustainable forest management.

References

Abushenko, N.A., V.V. Koshelev, N.P. Minko *et al*. (1998). Registration of forest fire by AVHRR/NOAA data for territories of East Russia. In: V.I. Sukhikh (ed.), *Air and Satellite Methods and Geographical Information Systems in Forestry and Forest Management*, Materials of the 2nd All-Russia Meeting, Moscow, 18–19 November 1998. RAS and Federal Forest Service, Moscow, pp. 170–171 (in Russian).

Ahern, F.J., A.C. Janetos and E. Langham (1998). Global observation of forest cover: A CEOS integrated observation strategy. Proceedings of 27th International Symposium on Remote Sensing of Environment, Tromsø, Norway, 8–12 June, pp. 103–105.

Antonovsky, M.Ja., V.M. Buhshtaber, L.S. Veksler and Zh.P. Malingro (1992). Statistical analysis of data on global vegetation index. Problems of ecological monitoring and ecosystems modeling. Vol. VI, St. Petersburg, *Hydrometeoizdat*, pp. 153–173 (in Russian).

Arkhipov, V.I., A.N. Sarmanaev and V.G. Alekhin (1992). Accounting and estimation of forest resources by remote methods. *Forestry*, No. 4–5, pp. 28–29 9 (in Russian).

Artzybashev, E.S. (1974). Forest fires and combating them. *Forest Industry*, 150 p. (in Russian).

Asmus, V.V., O.N. Grigoryeva, V.A. Krovotynzev and S.V. Shvarev (1998). Space monitoring of influence zone of projected railway in the North of Russia: Fragment of landscape cartographic base. In: A.S. Isaev and V.I. Sukhikh (eds.), *Aerospace Methods and Geoinformation Systems in Forestry and Forest Management*, Moscow, pp. 51–56 (in Russian).

Bakhtinova, E.V. and N.G. Fedorov (1987). Implementation of large-scale air-photo images the inventory of recreation forests. *Forestry*, No. 12, pp. 51–52 (in Russian).

Baranov, Yu.B., Yu.K. Korolev and S.A. Miller (1997). Software for remote sensing data processing. *Informational Bulletin of GIS-Association*, No. 2 (9), pp. 43–45 (in Russian).

Bartalev, S.A. (1998). Development of methods for processing of satellite images, geoinformation systems and GIS technologies to provide forest monitoring. In: A.S. Isaev and V.I. Sukhikh (eds.), *Aerospace Methods and Geoinformation Systems in Forestry and Forest Management*, Moscow, pp. 58–61 (in Russian).

Bartalev, S.A., V.M. Zhirin and D.V. Ershov (1995). Comparative analysis of data from satellite systems “Kosmos-1939”, SPOT and LANDSAT-TM for boreal forest investigations. *Issledovanija Zemli iz Kosmosa*, No. 1, pp. 101–114 (in Russian).

Berezin, V.I. (1995). Inventory of hydro-forest-melioration systems based on air space images. *Forestry*, No. 6, pp. 28–30 (in Russian).

Bodanskii, E.D., L.A. Kuzenkov and R.I. Elman (1984). Technological approach for automatization and thematic processing of images. *Issledovanija Zemli iz Kosmosa*, No. 1, pp. 92–100 (in Russian).

Breido, M.D. and V.M. Zhirin (1989). Determination of some characteristics of fodder resources in desert pastures by air space information. *Issledovanija Zemli iz Kosmosa*, No. 3, pp. 66–76 (in Russian).

Breido, M.D. and V.I. Sukhikh (1995). Registration of spatial changes by space images in boreal Russian forests caused by clear cuts. *Issledovanija Zemli iz Kosmosa*, No. 4, pp. 80–90 (in Russian).

Breido, M.D. and V.I. Sukhikh (1996). Use of space imagery to record geographical changes in the Russian boreal forests resulting from continuous felling. *Earth Obs. Rem. Sens.*, Vol. 13, pp. 617–630.

Breido, M.D., E.D. Bodanskii, O.L. Orlova and R.I. Elman (1992). Automatization of detection, registration and analysis of changes in forest funds by space images. Review information, VNIICLesresurce, 36 p. (in Russian).

Breido, M.D., A.G. Popik, D.V. Rakov, D.A. Starostenko and R.I. Elman (1995). Registration of the impacts of large scale forest fires by scanner space images. *Issledovanija Zemli iz Kosmosa*, No. 1, pp. 115–126 (in Russian).

Brukhanov, A.V., G.V. Gospodinov and Yu.F. Knizhnikov (1982). Aerospace methods for geographic research. Moscow State University, 232 p. (in Russian).

Butusov, O.B., B.V. Vinogradov and A.M. Stepanov (1996). Space monitoring of forests of South Ural with air pollution. *Lesovedenie*, No. 3, pp. 16–27 (in Russian).

Butusov, O.B., L.M. Nosova and A.M. Stepanov (1998). Analysis by remote sensing of recovering of forests after ecological catastrophes. *Izvestija* RAS, Series Geographical, No. 1, pp. 90–101 (in Russian).

Chimitdorzhiev, T.N. (1998). Development of the methods of space observation of regional ecosystems using the zone of Chernobyl ANPS as a case study. Institute of Radiotechnic and Electronic, Moscow, 17p. (in Russian).

Cihlar, J., J.M. Chen, Z. Li, F. Huang, R. Latifovic and R. Dixon (1998a). Can interannual land surface signal be discerned in composite AVHRR data? *J. of Geoph. Res.*, Vol. 103, No. D18, 23, 163-23, 172.

Cihlar, J., Qinghan Xiao, J. Chen, J. Beaubien, K. Fung and R. Latifovic (1998b). Classification by progressive generalization: A new automated methodology for remote sensing multichannel data. *Int. J. Remote Sensing*, Vol. 19, No. 14, pp. 2685–2704.

Danjulis, E.P. and V.M. Zhirin (eds.) (1989). Remote sensing in forestry. Moscow, 223 p. (in Russian).

de Gier, A., E. Wesunga, S. Beerns, P. van Laake and H. Savenije (1999). User requirements study for remote sensing based spatial information for the sustainable management of forests. Final Report, ITC, Netherlands, 25 p.

Dmitriev, I.D., E.S. Murahtanov and V.I. Sukhikh (1989). Forest aviation and air photo images. Moscow, 366 p. (in Russian).

Dobson, C.M., F.T. Ulaby, T. Le Toan, A. Beaudoin, E.S. Kasischke and N. Christinsen (1992). Dependence of radar backscatter on coniferous forest biomass. *IEEE Transactions in Geoscience and Remote Sensing*, 30(2), pp. 412–415.

Donchenko, V.V., N.I. Goltsova, O.M. Johansson *et al*. (1998). Synergistic use of SAR and other satellite data to monitor damaged areas of boreal forests for St. Petersburg region. Proceedings of 27th International Symposium on Remote Sensing of Environment, June 8–12, 1998, Tromsø, Norway, pp. 640–643.

Efimov, S.V. and S.A. Miller (1997). Russian space and Russian market for space data. In: GIS technologies. Management. Usage. Business. Moscow, 2–6 June. GIS-Association, pp. 218–230 (in Russian).

Efremenko, V.V. and A.V. Moshkov (1997). Method for detection of vegetation by spectrazonal scanner. *Issledovanija Zemli iz Kosmosa*, No. 6, pp. 3–9 (in Russian).

Elman, R.I. (1984). Scientific basis and directions for automatization of aerospace information processing on forests. International Training Seminar OON on Practical Application of Earth's Remote Sensing in Forestry. Moscow, 19 p. (in Russian).

Elman, R.I., L.A. Kuzenkov and E.D. Bodanskii (1984). Implementation of an automatic system for processing of space information on forests. *Forestry*, No. 6, pp. 53–55 (in Russian).

FFSR (1993). Concept of the forest inventory and planning. Decision of the Federal Service of Forestry of Russia on 25 June 1999. Moscow, 6 pp.

Filippchuk, A.N. (1998). Crises in the field of using remote sensing methods. In: A.S. Isaev and V.I. Sukhikh (eds.), *Aerospace Methods and Geoinformation Systems in Forestry and Forest Management*, Moscow, pp. 35–40 (in Russian).

Furyaev, V.V. (1991). Monitoring of the impacts of forest fires. *Aerospace Monitoring of Forests*, Moscow, pp. 122–135 (in Russian).

Furyaev, V.V. and D.M. Kireev (1983). Utilization of space images for estimation of forest damaged by fires. *Issledovanija Zemli iz Kosmosa*, No. 3, pp. 43–49 (in Russian).

Garbuck, S.V. and V.E. Gershenzon (1997). Space systems for earth remote sensing. Moscow, 296 p. (in Russian).

Gershenzon, V.E. and O.N. Tarakanova (1997). "Resource-0" scans the earth. The role of the Russian space program for operational monitoring of the earth's surface. *GIS-review*, No. 1, pp. 29–30 (in Russian).

Giryaev, M.D. (1998). Experience and perspectives of application of air and space information in forest management in Russia. In: V.I. Sukhikh (ed.), *Air and Satellite Methods and Geographical Information Systems in Forestry and Forest Management*, Materials of the 2nd All-Russia Meeting, Moscow, 18–19 November 1998. RAS and Federal Forest Service, Moscow, 6–13 (in Russian).

Goetz, S.J. and S.D. Prince (1996). Remote sensing of net primary production in boreal forest stand. *Agricultural and Forest Meteorology*, 78, No. 3, pp. 149–179.

Gusev, N.N. (1998). History of Russian forest inventory and planning. Moscow, Centrlesproect-group "Erko", 330 p. (in Russian).

Gusev, N.N. and S.G. Sinitsyn (1981). Forest inventory and planning in the USSR. Moscow, 328 p. (in Russian).

Hagner, O. (1990). Computer aided forest stand delineation and inventory based on satellite remote sensing. Proceedings from the SNS/IUFRO Workshop, 26–28 February 1990, Umeå.

Implementation of Satellite Information for Protection of Forests from Fires (1977). Practical recommendations. Moscow–Leningrad, 14 p. (in Russian).

Instruction on Forest Inventory and Planning in the Russian Forest Fund (1995). Part 1. Organization of forest inventory. Field works. Moscow, VNIICLesresurs. 175 p. (in Russian).

Investigation of Characteristics and Sustainability of Boreal Forests (1998). Report about the I and II stages. Joint Russian-American Commission on Economic and Technological Collaboration, 13 p. (in Russian).

Investigations of Taiga Landscapes by Remote Methods (1979). Novosibirsk, 170 p. (in Russian).

Isaev, A.S. (ed.) (1995). Problems of monitoring and modeling the dynamics of forest ecosystems. Moscow, 352 p. (in Russian).

Isaev, A.S. (ed.) (1997). Extraordinary program of biological struggle with insects in forests of Krasnoyarsk Krai. Moscow, 154 pp. (in Russian).

Isaev, A.S. and F.I. Pleshikov (1987). Main directions in investigations of Siberian forest resources by aerospace techniques. *Investigations of Forests by Aerospace Techniques*, Novosibirsk, pp. 3–9 (in Russian).

Isaev, A.S. and V.I. Sukhikh (1979). Conception of aerospace monitoring of forests. *Aerospace Monitoring of Forests*, Moscow, pp. 7–26 (in Russian).

Isaev, A.S. and V.I. Sukhikh (1986). Aerospace monitoring of forest resources. *Lesovedenie*, No. 6, pp. 11–21 (in Russian).

Isaev, A.S. and V.I. Sukhikh (eds.) (1991). Aerospace monitoring of forests. Moscow, 240 p. (in Russian).

Isaev, A.S. and V.I. Sukhikh (eds.) (1998). Aerospace methods and geoinformation systems in forestry and forest management. Moscow, 215 p. (in Russian).

Isaev, A.S., V.V. Kiselev and Yu.P. Kondakov (1991). Forest-pathological monitoring. *Aerospace Monitoring of Forests*, Moscow, pp. 135–154 (in Russian).

Kalashnikov, E.N. and F.I. Pleshikov (1991). General principles for monitoring of natural and anthropogenic processes. *Aerospace Monitoring of Forests*, Moscow, pp. 73–76 (in Russian).

Kalashnikov, E.N., N.V. Malysheva and V.I. Sukhikh (1991). Cartographic support for monitoring. *Aerospace Monitoring of Forests*, Moscow, pp. 36–63 (in Russian).

Kapitsa, A.P. and E.I. Golubeva (1995). Bioindicators for disturbances of tundra ecosystems. Paper presented at the IGU Conference "Global Change and Geography", Moscow (in Russian).

Kennedy, P. and S. Folving (1997). FIRS — Forest information from remote sensing. Status Report. JRS, European Comission, 24 p.

Kharuk, V.I. and K. Vintenberger (1995). Analysis of technogenic degradation of near-tundra forests by space images. *Issledovanija Zemli iz Kosmosa*, No. 4, pp. 91–97 (in Russian).

Kharuk, V.I., K.J. Ranson, T.A. Burenina and E.F. Fedotova (1998). Radar exploration of taiga forests. *Forest Science* (submitted).

Kireev, D.M. (1977). Methods for forest investigations by space images. Novosibirsk, 212 p. (in Russian).

Kireev, D.M. (1992). Landscape mapping of forests. Moscow–St. Petersburg. VNIICLesresurs, 60 p. (in Russian).

Knizhnikov, Yu.F. (1997). Aerospace sounding. Methodology, principles, and problems. Studying material. Moscow State University, 129 p. (in Russian).

Kondratyev, K.Ja. and V.V. Melentyev (1995). Experiences of practical use of ERS-1 SAR — images for monitoring and improvement of hydrometeorological data for ice navigation in the Northern passage. *Issledovaniia Zemli iz Kosmosa*, No. 1, pp. 74–88 (in Russian).

Konstantinov, V.D. and S.M. Gorozhankina (1991). Monitoring of ecological regimes of taiga ecosystems. *Aerospace Monitoring of Forests*, Moscow, pp. 76–95 (in Russian).

Korolev, Yu.K. and Yu.B. Baranov (1996a). Market for remote sensing data (Marketing-technological review). *Informational Bulletin of GIS-Association*, No. 1 (3), pp. 66–75 (in Russian).

Korolev, Yu.K. and Yu.B. Baranov (1996b). Methods for remote sensing data processing. *Informational Bulletin of GIS-Association*, No. 2 (4), pp. 51–55 (in Russian).

Kravtsov, Yu.A. and A.V. Kuzmin (1997). Polarization peculiarities of radio-location images. *Issledovaniia Zemli iz Kosmosa*, No. 6, pp. 43–55 (in Russian).

Krinov, E.L. (1947). Spectral reflectance of natural objects. Moscow–Leningrad, 271 p. (in Russian).

Kukuev, Yu.A. (1998). Problems with providing sustainable development of Russian forestry. *Forest Management*, No. 2, pp. 41–43 (in Russian).

Landscape Methods in Forest Mapping (1987). Krasnoyarsk. IliD SB AS USSR, 114 p. (in Russian).

Lavrov, V.N. (1997). Use of Russian space images for mapping and GIS. Proceedings from the forum “GIS-Technologies. Management. Usage. Business”. Moscow, 2–6 June. Moscow GIS-Association, pp. 91–92 (in Russian).

Le Toan, T., A. Beaudoin and D. Guyon (1992). Relating forest biomass to SAR data. *IEEE Transactions on Geoscience and Remote Sensing*, 30, pp. 403–411.

Luckman, A., J. Baker, M. Hoznak and R. Lucas (1998). Tropical forest biomass density estimation using JERS-1 SAR: seasonal variation, confidence limits and application to image mosaics. *Remote Sens. Environ,*. Vol. 63, pp. 126–139.

Malysheva, N.V. (1996). Aerospace monitoring of forests in the water-protected zone of Lake Baikal (Theoretical background, methodology, working experience). Review Information, Vol. 10, Moscow, VNIICLesresurs, 34 p. (in Russian).

Malysheva, N.V. and V.I. Sukhikh (1991). Mapping of potential centers of entomological pests. *Aerospace Monitoring of Forests*, Moscow, pp. 154–163 (in Russian).

Malysheva, N.V., S.V. Knyazeva, N.E. Raichenko, L.V. Babenko and T.A. Zolina (1997a). Map of the current state of the forests in the Lake Baikal basin. Proceedings of the VII Annual Conference MAIBL "Sustainable Development of Boreal Forests", Moscow, pp. 71–73 (in Russian).

Malysheva, N.V., S.V. Knyazeva, V.I. Sukhikh and V.M. Shirin (1997b). Maps of forests with ecological content. Methodology and experience of development. Proceedings of Jub. Sci.-tech. Conference "Present State and Perspectives for Development of Geodesy, Photo-Topography, Cartography, and GIS". Moscow, CNIIGAiK, pp. 154–163 (in Russian).

Methodology for Remote Control of Changes in the Forest Fund Caused by Oil Exploiting and Extraction (1990). Moscow, VNIICLesresurs, 13 p. (in Russian).

Methodology for Small-scale Mapping of Forest Fund Based on Space Images (1981). Moscow, CBNTILesxoz, 8 p. (in Russian).

Miheev, V.S., A.K. Cherkashin and A.D. Kitov (1996). Methods for land evaluation by using remote sensing data and GIS-technologies. Proceedings of International Conference "Intercarto-2: GIS for studying and mapping of nature", Irkutsk, 26–29 June, pp. 152–154 (in Russian).

Milov, Yu.G. and V.I. Kozlov (1997). Space systems for remote sensing of Earth's surface. "Resource-DK" — for solving problems in Russian Regions. Proceedings of Forum "GIS-Technologies. Management. Usage. Business", Moscow, 2–6 June. Moscow GIS-Association, pp. 98–99 (in Russian).

Nilsson, S. and A.Z. Shvidenko (1998). Is sustainable development of the Russian forest sector possible? IUFRO Occasional Paper No. 11, ISSN 1024-414X, 76p.

Nilsson, S. *et al*. (2000). Full carbon account for Russia. IIASA Interim Report IR-00-021. International Institute for Applied Systems Analysis, Laxenburg, Austria, forthcoming.

Orlova, O.L. and I.A. Vukolova (1997). Estimation of post-harvesting dynamics of forest ecosystems by aerospace information and GIS technologies. Proceedings of VII Annual Conference MAIBL "Sustainable Development of Boreal Forests". Moscow, pp. 74–77 (in Russian).

Pavlichenko, E.A., S.I. Miskiv and V.J. Romasko (1998). Detection of forest fire by remote sensing methods from NOAA satellites and data base formation in GIS ARCVIEW. In: V.I. Sukhikh (ed.), *Air and Satellite Methods and Geographical Information Systems in Forestry and Forest Management*, Materials of the 2nd All-Russia Meeting, Moscow, 18–19 November 1998. RAS and Federal Forest Service, Moscow, 190–194 (in Russian).

Pleshikov, F.I. and V.P. Cherkashin (1996). GIS-technologies for forest monitoring and forestry management. Proceedings of International Conference "Intercarto-2: GIS for studying and mapping of nature", Irkutsk, 26–29 June, pp. 174–177 (in Russian).

Pleshikov, F.I. and V.A. Ryzhkova (1991). Control of the dynamics of forest recovering processes at glades. *Aerospace Monitoring of Forests*, Moscow, pp. 163–180.

Pleshikov, F.I., V.A. Ryzhkova and V.Ja. Kaplunov (1991). Assessments of forest growth conditions. *Aerospace Monitoring of Forests*, Moscow, pp. 95–110 (in Russian).

Pleshikov, F.I., E.N. Kalashnikov, V.A. Ryzhkova, V.P. Cherkashin and V.Ja. Kaplunov (1996a). Studying and mapping of current state of forests in middle Siberia using geoinformaton technologies. In: Intercarto-2: GIS for Studying and Mapping of Environment. Irkutsk, p. 172–174 (in Russian).

Pleshikov, F.I., V.P. Cherkashin, V.A. Ryzhkova and V.Ja. Kaplunov (1996b). Geoinformation technologies in solving problems of forest monitoring and forest management. In: Intercarto-2: GIS for Studying and Mapping of Environment. Irkutsk, p. 174–177 (in Russian).

Polshvedkin, P.V., V.I. Stepanemko, V.N. Prokhorov, E.P. Gerasimov and O.I. Popova (1998). Preparation to acquisition and use of satellite information in forest management of the Republic Komi by means of GIS-technologies. In: V.I. Sukhikh (ed.), *Air and Satellite Methods and Geographical Information Systems in Forestry and Forest Management*, Materials of the 2nd All-Russia Meeting, Moscow, 18–19 November 1998. RAS and Federal Forest Service, Moscow, 79–82 (in Russian).

Ponomarev, E.I. and A.I. Sukhinin (1998). Information from NOAA satellite for assessment of forest fire risk by weather conditions. In: V.I. Sukhikh (ed.), *Air and Satellite Methods and Geographical Information Systems in Forestry and Forest Management*, Materials of the 2nd All-Russia Meeting, Moscow, 18–19 November 1998. RAS and Federal Forest Service, Moscow, 194–196 (in Russian).

Project on Management of Environment of the Russian Federation (1997). World Bank Loan 3806-RU. Program of extraordinary measures on biological struggle with pests in forests of the Krasnoyarsk krai. Final Report, Moscow, 144 p. (in Russian).

Project on Studies of Characteristics and Sustainability of Boreal Forests (1998). Report on the 1st and 2nd Stages. Joint Russian-American Commission on Economic and Technological Cooperation, Moscow, 13 p. (in Russian).

Ranson, K.J. and G. Sun (1997). An evaluation of AIRSAR and SIR-CX-SAR images for mapping Northern forest attributes in Maine, USA. *Remote Sens. Env*., No. 59, pp. 203–222.

Rees, W.G. and M. Willams (1997). *Satellite remote sensing of the impact of industrial pollution on tundra biodiversity. Disturbance and recovery in Arctic lands*. Kluwer Academic Publisher, pp. 253–279.

Regina, O. (1998). Detection of pollution-induced forest decline in the Kola peninsula using remote sensing and mathematical modelling. Swedish University of Agricultural Science, Repport 9, 81 p.

Remote Identification of Taiga Landscape Structure (1981). Novosibirsk, 103 p. (in Russian).

Remote Investigations of Landscapes (1987). Novosibirsk, 199 p. (in Russian).

Rjapolov, V.Ja. (1985). Methodology for construction of maps on forests damaged by insects-pests. *Geography and Natural Resources*, No. 2, pp. 97–107, (in Russian).

Samoilovich, G.G. (1964). Implementation of aviation and air photo shooting in forestry. Moscow, 484 p. (in Russian).

Schmullius, C. and A. Rosenquist (1997). Closing the gap-a Siberian boreal forest map with ERS-1/2 and JERS-1. Proceedings of 3rd ERS Symposium on Space at the Service of our Environment, Florence, Italy, 17–21 March 1997 (ESA SP-414, 3 Vols., May 1997), pp. 1885–1990.

Sedykh, V.N. (1991). Aerospace monitoring of forest cover. Novosibirsk, 238 p. (in Russian).

Sedykh, V.N. (1996). Forests of Western Siberia and oil-gas complexes. Moscow, *Ecology Series*, Issue 1, 36 p. (in Russian).

Sedykh, V.N. (1999). Ecological problems of forests in West Siberia. *Forest Management Information*, No. 3–4, VNIIZlesresurs, Moscow, 24–41 (in Russian).

Selivanov, A.S. and Yu.M. Tuchin (1988). The operational system “Resource-01” for Earth observations. *Issledovaniia Zemli iz Kosmosa*, No. 3, pp. 101–106 (in Russian).

Shubin, V.A. (1998). Targets of Russian foresters in the New Year. *Forest Management*, No. 1, 2–5 (in Russian).

Shvidenko, A.Z. and S. Nilsson (1997). Are the Russian forests disappearing? *Unasilva*, Vol. 48, No. 1, pp. 57–64.

Skole, D.L., W.A. Salas and V. Taylor (eds.) (1998). Global observation of forest cover. Fine resolution data and product design strategy. Report of a Workshop, 23–25 September 1998, Paris, France. Appendix 3 and 4: Fine resolution design team report and coarse resolution design report, 51 pp.

Steffen,W., J. Canadell, M. Apps, E.-D. Schulze, *et al*. (1998). The terrestrial carbon cycle: Implications for the Kyoto Protocol, *Science*, Vol. 280, 29 May, p. 1393–1394.

Stocks, B. and J.K. Goldammer (1997). International collaboration in investigations of fires in boreal forests. Proceedings of the VII Annual Conference MAIBL “Sustainable Development of Boreal Forests”, pp. 143–147.

Strakhov, V.V., A.N. Filippchuk and A.Z. Shvidenko (1995). On reform of forest inventory in Russia. *Forest Management* (*Lesnoe khozjaistvo*), No. 1, 11–14 (in Russian).

Strakhov, V.V., A.N. Filippchuk and A.Z. Shvidenko (2001). Sustainable development of the Russian forest sector and strategy of forest inventory. *Forest Management* (*Lesnoe khozjaistvo*), No. 5 (*in press*) (in Russian).

Streltsov, V.A. and V.A. Gorelov (1990). Ways for increasing the efficiency of space images for earth natural resource investigations. Review information, Issue 2. Moscow, CNIIGAIK, 64 p. (in Russian).

Sukhikh, V.I. (1995). The use of satellite information for forest study and evaluation in Russia. In: R. Kuittinen (ed.), *Proceedings of the Finnish-Russian Seminar on Remote Sensing in Helsinki*, 29 August–1 September, 1994, pp. 65–72.

Sukhikh, V.I. (1996). Assessment of the informativeness of high-resolution space photographs in the inventarization of forests. *Earth Obs. Rem. Sens.*, Vol. 14, pp. 229–245.

Sukhikh, V.I. (1998). Air and satellite methods and geo-information systems in forestry and forest management of current Russia. In: V.I. Sukhikh (ed.), *Air and Satellite Methods and Geographical Information Systems in Forestry and Forest Management*, Materials of the 2nd All-Russia Meeting, Moscow, 18–19 November 1998, RAS and Federal Forest Service, Moscow, 27–32 (in Russian).

Sukhikh, V.I. and S.G. Sinitsyn (eds.) (1979). Air-space methods for nature preservation and forestry. Moscow, Forest Industry, 228 p. (in Russian).

Sukhikh, V.I. and V.M. Zhirin (1996). Estimation of the information content of high resolution space photo images for forest inventory. *Issledovaniia Zemli iz Kosmosa*, No. 2, pp. 45–56 (in Russian).

Sukhikh, V.I., N.N. Gusev and E.P. Danjulis (1977). Air methods in forest management. Moscow, 192 p. (in Russian).

Sukhikh, V.I., P.A. Kropov and V.A. Maksimov (1981). Methods for small-scale mapping of the Forest Fund based on space photo images. Moscow, 23 p. (in Russian).

Sukhikh, V.I., E.P. Danjulis and R.I. Elman (1982). Methods for forest resource investigations from space. In: Ways for increasing the efficiency of forest management. Moscow, pp. 58–113 (in Russian).

Technical Instructions on the Inventory of Woody Shrub Vegetation of Deserts Based on Air Photo Images (1985). Moscow, 8 p. (in Russian).

Technical Training of Specialists for Inventory-decoding (1995). In: Practical Appliances on Forest Assessments, Contours, and Field Decoding of Air Photo Images. St. Petersburg, pp. 10–64 (in Russian).

Tjurin, E.G. (1991). Examining glades from large-scale air images. *Forestry*, No. 1, pp. 40–42 (in Russian).

Tompo, E. (1997). Multi-source national forest inventory of Finland. To be published in (ISPRE) JRC Series.

Treifeld, R.F. (1998). Forest inventory and planning based on air and satellite information and GIS-technologies. In: V.I. Sukhikh (ed.), *Air and Satellite Methods and Geographical Information Systems in Forestry and Forest Management*, Materials of the 2nd All-Russia Meeting, Moscow, 18–19 November 1998. RAS and Federal Forest Service, Moscow, 92–99 (in Russian).

Trifonov, Yu.V. (1981a). Satellites of “Meteor”. Investigations of earth from space. *Issledovaniia Zemli iz Kosmosa*, No. 5, pp. 8–20 (in Russian).

Trifonov, Yu.V. (1981b). Technical means for experiments of remote sensing of the earth. *Issledovaniia Zemli iz Kosmosa*, No. 5, pp. 21–27 (in Russian).

Vaganov, E.A. and E.S. Petrenko (1997). Russian-American project on forest management in Southern taiga of Krasnoyarsk Krai, based on ecosystem approaches. Proceedings of the VII Annual Conference “Sustainable Development of Boreal Forests”. Moscow, pp. 20–29 (in Russian).

Valendik, E.N. (1996). Strategy for fire prevention of Siberian forests. *Forestry*, No. 3, pp. 12–15 (in Russian).

Valendik, E.N. and A.I. Sukhinin (1991). System for forecasting and observations of forest fires. *Aerospace Monitoring of Fforests*, Moscow, pp. 110–122 (in Russian).

Varjo, J. (1997). Change detection and controlling forest information using multi-temporal Landsat TM imagery. *Acta Forestalia Fennica*, Vol. 258, 64 p.

Vukolova, I.A. and O.L. Orlova (1997). Assessment of forest recovering on glades by remote methods. In: Problems of Forest Organization. Moscow, VNIILM, pp. 93–99 (in Russian).

Vygodskaya, N.N. and I.I. Gorshkova (1987). Theory and experiment in remote sensing of vegetation. Leningrad, 248 p. (in Russian).

Walter, F. (1998). Remote-sensing for forestry planning. Redogörelse Nr. 9. The Forestry Research Institute, Uppsala, Sweden.

Wegmueller, U. and C.L. Werner (1995). SAR interferometric signatures of forest. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 33, No. 5, pp. 1153–1161.

Wegmueller, U. and C.L. Werner (1997). Retrieval of vegetation parameters with SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 35, No. 1, pp. 18–24.

Zaharov, A.I. and L.E. Nazarov (1998). Classification of forest types based on analysis of texture characteristics by the radio locative images RSA SIR-C. *Issledovaniia Zemli iz Kosmosa*, No. 2, pp. 102–109 (in Russian).

Zhirin, V.M. (1984). Technology for inventory of woody shrub vegetation of deserts. International study seminar OON on practical implementation of Earth remote sensing in forestry. Moscow, 20 p. (in Russian).

Zhirin, V.M. (1991). Control of the conditions of desert vegetation. *Aerospace Monitoring*, Moscow, pp. 218–230 (in Russian).

Zhirin, V.M. (1998a). Remote methods for forest state assessments. Thesis for Doctor of agricultural sciences. Brjansk, 37 p. (in Russian).

Zhirin, V.M. (1998b). Approximate estimate of phytomass of forest (vegetation) cover by values of vegetation index. In: V.I. Sukhikh (ed.), *Air and Satellite Methods and Geographical Information Systems in Forestry and Forest Management*, Materials of the 2nd All-Russia Meeting, Moscow, 18–19 November 1998. RAS and Federal Forest Service, Moscow, 119–122 (in Russian).

Zhirin, V.M. and O.L. Orlova (1985). Methods for estimation of forest recovering and formation of undergrowth in taiga zones glades by air space images. In: New methods for collection and processing of information in forest inventory. Moscow, pp. 29–32 (in Russian).

Zhirin, V.M., S.A. Bartalev and D.V. Ershov (1995). Spectrometric estimation of the conditions of woody vegetation by forest monitoring. In: Monitoring and modeling of dynamics of forest ecosystems. Moscow, pp. 24–42 (in Russian).

Zhirin, V.M., V.I. Sukhikh and S.P. Eydlina (1996). Dynamic vegetation index and landscape peculiarities of vegetation cover. *Issledovaniia Zemli iz Kosmosa*, No. 4, pp. 29–41 (in Russian).

Appendix 1

Table A1-1: List of normative and methodical documents regulating the use of remote methods in forestry practice.

No.	Name of instruction or method	Year of approval and issuing body
1	Temporal methodic instructions on statistical inventory of reserved forests based on aerospace images.	1978, Gosleshos USSR
2	Detection and mapping of recent glade areas by space images (Practical recommendations).	1979, NTS of Gosleshos USSR
3	Methods for small-scale mapping of Forest Fund based on space photographs (forest map of Mongolia Republic as an example).	1979, Gosleshos USSR
4	Temporal rules for usage of large-scale air photo images for detection of the conditions of harvest areas.	1981 Gosleshos USSR
5	Technical instructions for usage of space images for detection of changes in the Forest Fund caused by industrial activities and natural calamities.	1982, Gosleshos USSR
6	Temporal instructions on inventory of less exploited forests based on space images and data on previous forest management..	1983, Gosleshos USSR
7	Technical instructions on inventory of woody shrub vegetation in deserts based on aerospace images.	1984, Gosleshos USSR
8	Guide on small-scale mapping of forests by space images and cartographic material for forest inventory.	1986, Gosleshos USSR
9	Methods for organization and conduction of space-visual observations in order to prevent forests from fires.	1986, Minleshos RSFSR
10	Implementation of aerospace images for analysis of hydro-melioration (Methodical recommendations).	1986, Gosleshos USSR
11	Technical instructions for reserved forests inventory based on aerospace images.	1988, Gosleshos USSR
12	Methods for remote control of changes in Forest Fund caused by exploration of oil and gas.	1990, Goskomles USSR
13	Technical instructions on technology for aerospace inventory of woody shrub vegetation and estimation of fodder resources in desert zone.	1990, Goskomles USSR
14	Instruction on forest management conduction in Russia forest fund. Part I. Organization of forest management. Field work.	1994, Federal Service of Forestry of Russian Federation

Table A1-2: List of methodological documents approved for implementation in forestry practice.

No.	Name of method	Year of approval and issuing body
1	Methods for estimation of forest recovering state and undergrowth forest formation in glades of the taiga zone by using space images and selected large-scale air photo images.	1983, Scientific Council V/O Lesproect
2	Methods for estimation of deviations from the main Rules for Harvests based on space images.	1985, Scientific Council V/O Lesproect
3	Temporal method for assessment of plantations influenced by industrial pollutants.	1986, Scientific Council VNIILM
4	Methodological recommendations for implementation of aerospace images in the inventory of protection plantations in agricultural lands.	1986, Scientific Council V/O Lesproect
5	Methods for data collection on the condition of plantations in industrially polluted zones by large-scale air photo images (the mountain forests of water-protected area of the Lake Baikal is an example).	1995, Scientific Council VNIICLesresurs
6	Methodological recommendations on conduction of flights for air images and on implementation of video information in forest monitoring.	1995, Scientific Council VNIIC Lesresurs
7	Methods for determination of indices on sustainability based on space images.	1995, Scientific Council VNIICLesresurs
8	Methodological recommendations for development of forest maps at the scale of 1:1000000 based on space images (like the water-protected zone of Lake Baikal).	1995, Scientific Council VNIICLesresurs

Appendix 2: List of Organizations Developing Remote Sensing Methods for Forestry in the CIS

	Organization	Main area of investigation and previous projects
	RUSSIA: Russian Academy of Sciences (RUS)	
1	Center on Problems of Ecology and Productivity of Forests RAS, Moscow. International Forest Institute RAEN.	Theory and methods for aerospace monitoring, automatic processing of remote data, GIS. The project Management of Natural Environments of Russian Federation, World Bank Loan 3806-RU, 1997. The Project on Investigations of Characteristics and Sustainability of Boreal Forests, EWG Boreal Forest Study, 1998. Remote diagnostics of forest ecological state in zones of industrial (including chemical) pollution, South Ural (Project RFFR 95-0411478). Contract with Russian Space Agency on participation in Russian-French Project on implementation of space images (Satellites SPOT and KBP-1000) and GIS for forest inventory and monitoring.
2	V.N. Sukachev Forest Institute, SBRAS, Krasnoyarsk.	Decoding of remote data and mapping of landscapes. Ecological mapping. Strategy and methods to forest fire prevention. GIS. Automatic image processing. The project FIRESCAN and monitoring of post-fire dynamics. Russian-American Project on forest management. Creation of 3-level GIS “Forests of Middle Siberia” with remote information.
3	V.N. Sukachev Forest Institute Western Siberian Department, RAS, Novosibirsk.	Decoding and mapping of forests on landscape basis. Elaboration of methods for monitoring of forest ecosystems in oil and gas exploring regions.
4	Geographic Institute SB RAS, Irkutsk.	Searching Investigations on estimations of forest and agricultural lands by remote information and GIS technologies. Russian-American project on land-use policies for Russian territory in the Lake Baikal basin.
5	Radiotechnic and Electronic Institute RAS, Moscow.	Basic research on estimation of information content of radio-location and operational scanner images for classification of forest vegetation. Algorithms for automatic image processing.

6	Geographic Institute RAS, Moscow.	Implementation of satellite information and GIS for studies of geographic condition. Basic investigations of spectral and polarization characteristics of vegetation. The International Project MSU-WCMC-SPRI, 1994.
	Russian Higher Educational Institutions	
7	M.V. Lomonosov Moscow State University (MSU) Geographic Department. Laboratory of Aerospace Methods. Moscow.	Teaching on the specialities of aerospace sounding and cartography. Construction of thematic atlases using remote information. International project MSU-WCMC-SPRI, 1994.
8	Institute of System Analysis of Forest attached to Moscow State University of Forest, Mytischi, Moscow Region.	Investigations on automatic processing of remote data for forests studies. Processing of video images taken by cosmonauts on board of the orbital space station “MIR”.
	Russian Federal Service of Forestry	
9	St. Petersburg Scientific-Research Institute of Forestry, St. Petersburg.	Applying remote information for rational organization of forest fire prevention. Elaboration of methods for visual and instrumental decoding of air-photo images for forest inventory. Construction of stereo apparatus.
0	All-Russian Scientific-Research and Informational Center for Forest Resources (VNIICLesresurs), Moscow.	Elaboration of methods for decoding and mapping of forest ecosystems based on remote information. Elaboration of methods for aerospace monitoring of forests in the watershed of Lake Baikal. Elaboration of methods for forest ecological monitoring using aerospace tools and GIS-technologies. The project TASIS FDFUS 9507 “Management of the forest resources in Russian North-West: Karelian Project” (current). The project “Video Monitoring” — management of environments of Russian Federation, World Bank Loan 3806-RU, 1996–1997.
11	Aerospace expedition attached to VNIICLesresurs, Moscow.	Photo statistical inventory of reserved forests. Examination of harvested areas by using large-scale air photo shooting.
12	All-Russian Scientific Research Institute of Fire-Prevention Protection of Forests and Mechanization of Forestry (VNIIPOMLeshoz), Krasnoyarsk.	Applied research on implementation of space information for organization of forest fire protection.

3	North-West State Forestry Enterprise, St. Petersburg.	Photo-static inventory of reserved forests. Inventory of hydro-meliorative systems, and technical condition of forest-drainage network.
14	Eastern-Siberian State Forestry Enterprise, Krasnoyarsk.	Elaboration of methods and large-scale air photos of forests from helicopters.
15	Western-Siberian State Forestry Enterprise, Novosibirsk.	Implementation of new methods for forestry by using small-scale air photos.
16	State center “Priroda” and affiliates.	Complex inventory and mapping of natural resources, ecological mapping.
	UKRAINE	
17	Scientific-Research Center of Aerospace Information and Ecological Monitoring affiliated with the V.M. Glushkov Institute of Cybernetics, National Academy of Sciences of Ukraine, Lyvov.	Video monitoring of forestry and agriculture. Investigations on processing of images taken by Ukrainian satellite “Sich-1” launched in 1995.
18	Centre for Aerospace Researchers of the Earth, National Academy of Sciences of Ukraine	Modeling satellite data processing and interpretation for ecological and resource assessments. Monitoring of zone affected by the Chernobyl accident.
	BELORUSSIA	
19	Institute of Physics of Belorussian Academy of Sciences.	Elaboration and testing of spectropolarimetrical technologies for remote and ground-based sounding.
20	Scientific-Research Institute of Applied Physical Problems affiliated with Belorussian State University.	Testing and construction of technologies.

Appendix 3: Major Satellites and Sensors for Forestry Applications

The main satellites and sensors currently used in different operational forest applications include Landsat with its TM sensor, SPOT with its multispectral XS and XI sensors, and “Resource-01” with its MSU-E and MSU- SK instruments. Other sensors used are also, for example, NOAA/AVHRR, IRS 1C/D and Radarsat. In the coming years a number of new sensors will be launched. A selection of important current and future sensors for forest applications is given below.

Landsat 7 was launched on 15April 1999. The satellite, managed in cooperation between NASA, NOAA, and USGS, and operated by NOAA, carries an enhanced version of the TM instrument on Landsat 4 and 5, called the Enhanced Thematic Mapper Plus (ETM+). The main features of the ETM+ are as follows:

Band	**Spectral range (µm)**	**Ground resolution (m)**
1 (Blue)	.450 – .515	30
2 (Green)	.525 – .605	30
3 (Red)	.630 – .690	30
4 (Near IR)	.750 – .900	30
5 (Mid IR)	1.55 – 1.75	30
6 (Thermal IR	10.4 – 12.5	60
7 (Mid IR)	2.09 – 2.35	30
Panchromatic	.520 – .900	15

The new pricing policy for data from Landsat 7 will make TM data interesting for a number of forest applications where price so far has been the bottleneck.

SPOT 4 was launched 24March 1998. SPOT 4 offers a number of improvements over its three predecessors, including the addition of a short wave infrared (i.e., mid IR) band, independent programming and acquisition of the two HRV-IR instruments, increased recording capability of the two tape recorders and the addition of a solid state memory. In order to allow on-board registration of all bands, the 10 meter panchromatic band on SPOT 1–3 has been replaced on SPOT 4 by 10 and 20 meter sampling of band 2 (red).

IRS-1D was launched on 29September 1997 by the Indian Space Research Organization (ISRO). The satellite is identical to IRS-1C, launched in December 1995. Thus, this pair of satellites taken together gives a periodicity of 12 days as opposed to the single-satellite 24-day observation cycle. The satellite carries instruments with both high and medium spatial resolutions.

NOAA/AVHRR has obvious advantages, such as the operative character of information, large territories and high periodicity of observations, as well as shortcomings such as limitations on resolution (1.1×1.1 km in nadir and about 15 km at the edge of the scanning zone), and the impossibility of observation of cloud covered areas (although advanced technologies to improve received data have been suggested — cf. Cihlar *et al.*, (1998a,b)). AVHRR has 4 IR bands and 1 visible band (0.58–0.68 mkm). Under realistic conditions, burned areas of 200000 m^2 can be identified with a probability of about 0.9. The third channel is most appropriate for fire recognition. Based on analysis of the forest fire in Krasnoyarsk Krai, it has been shown that: (1) data from AVHRR is a very useful supplement to fire protection aircraft; (2) the reliability of fire recognition from fire protection aircraft is about 0.6–0.8; (3) fire areas are overestimated for small (<100 ha) and underestimated for big (>10000 ha) fires; (4) modernization of recognition algorithms is needed (Pavlichko *et al*., 1998). The reliability of the system as used in the Irkutsk oblast, is estimated to be somewhat higher, but the corresponding algorithm used by-pixel aggregation of data (Abushenko *et al*., 1998). There are interesting methodical developments which allow to estimate forest danger in forests based on weather conditions; the radiation temperature of surface (presented by NOAA in band of 11.5–12.5 µm) is used (Ponomarev and Sukhinin, 1998). Zhirin (1998b) showed that NDVI could be used for estimation of phytomass in low productivity ecosystems in Jakurtia (to 3 kg/m^2 of dry matter). There are more than 10 operational receiving stations from NOAA/AVHRR in Russia.

Two Russian "**Resource-01**" satellites are currently in orbit (Nos. 3 and 4, launched in 1994 and 1997 respectively). Sensors of these satellites include two types of multi-spectral scanning devices which work simultaneously. These cover five medium resolution channels (140–170 m) on the MSU-SK scanner and three high resolution channels (30–40 m) on the MSU-E scanner. The fields of observation of MSU-E could be re-aimed inside of those of MSU-SK (by commands from the Earth) which allows for the extrapolation of data resulting from the decoding of MSU-SK images and to decrease the period between two consequent observations (normally about 3 days for MSU-SK and about 20 days for MSU-E). The MSU-SK scanner has an infrared channel (10–12 µm) with a resolution of 660 m from the height 835 km (Resource-01 No. 4). The radiometric accuracy of temperature measurements is 0.5^{o}K, which is higher than that for NOAA, the closest analog. A very important property of MSU-SK is a conical scanning, which provides the same resolution and atmospheric impact over the entire observation area. This is because the beam length is constant for all elements of the scene. The second infrared channel (3.5–4.1 µm) is used for recognition of high temperature objects such as forest fires. Decoding of MSU-E imges for northern taiga zone in West Siberia allow the identification of the following forest classes: (1) immature and mature larch forests; (2) immature and mature cedar pine (*Pinus sibirica*) forests; (3) young and middle aged pine forests; (4) immature and mature pine forests; (5) immature and mature birch forests; (6) immature and mature spruce stands; (7) lichens pastures; and (8) bogs (Selivanov and Tuchin, 1988; Asmus *et al*., 1998).

The space lidar system **BALKAN,** developed by the RAS Institute of Atmospheric Optics (Tomsk), has been located aboard the MIR space station and can measure important parameters of the stratosphere, troposphere, clouds, ocean and land surfaces, and could be used for environmental monitoring of the atmosphere and for forest fire detection. A series of airborne lidars (ATMARIL-3, MEL-7000, TRAL-3000) could be used for the environmental monitoring of the atmosphere.

The Russian **OKEAN-O** satellites will replace OKEAN-O1 series. OKEAN-O No. 1 is scheduled for launch in late 1999. In comparison with OKEAN-O1, the new satellite will have enlarged and improved spaceborne instruments, including a high resolution multichannel MSU-V scanner and 2 medium resolution multichannel MSU-SK scanners.

ENVISAT is planned for launch in May 2000. The satellite will carry 9 instruments for a multidisciplinary mission with both scientific and applied objectives. This satellite continues and extends the ERS-1 and ERS-2 mission objectives, building up a coherent European Earth observation program.

IKONOS 2, equipped with very high resolution (VHR) optical sensors, is scheduled for launch before the end of 1999. IKONOS 2 will have both cross-track and along-track viewing instruments which will enable flexible data acquisition and frequent revisiting capability: 3 days at 1 meter resolution (for look angles <26°) and 1.5 days at 1.5 meter resolution. The near real-time programming capability will make it possible to program acquisitions while taking the current weather conditions into account. The nominal image width at nadir is 11 km. The sensor characteristics are shown below:

Band	**Spectral range (mm)**	**Spatial resolution (m)**
1 (Blue)	.450 – .520	4
2 (Green)	.520 – .600	4
3 (Red)	.630 – .690	4
4 (Near IR)	.760 – .900	4
Panchromatic	450 – .900	1

OrbView-3 is another VHR satellite that will offer optical imagery. The satellite will provide 1 and 2 meter panchromatic resolution images and 4 meter multispectral resolution images on a real-time basis worldwide. Launch is scheduled to take place early 2000. The spectral characteristics of the panchromatic and 4 multispectral bands on OrbView-3 are identical to those of IKONOS.

OrbView-4, planned for launch in 2000, will continue ORBIMAGE's line of high resolution satellites. It offers the same possibilities as OrbView-3 but will also be the world's first satellite to acquire hyperspectral images.

ALOS, the Advanced Land Observing Satellite, will be launched in early 2003 by NASDA in Japan. The satellite contains L-band SAR as used on JERS-1 and AVNIR as used on ADEOS. It will carry out high resolution observation of the earth's surface to help in the process of compiling maps. It is equipped with PRISM, a 2.5 m-capable triplet optical radiometer, AVNIR-2 (Advanced Visible Near-Infrared Radiometer, a successor to the AVNIR carried aboard ADEOS), and PALSAR, an L-band synthetic aperture radar.

Appendix 4: Examples of Operational Uses of Satellite Imagery in Nordic Forestry

Application of remote sensing information is until currently mostly based on manual interpretation of analog or digital imagery. During the last ten years, the digital processing of satellite data is being more frequently used. Remote sensing is utilized in Nordic forestry in applications such as:

- Forest inventory.
- Image background in analog and digital forest maps.
- Active support in planning of logging activities.
- Monitoring of performed logging and silvicultural activities.

Black-and-white aerial photos are currently the most common information source for producing forest inventories. Operational use of satellite data in different forest applications is growing rapidly.

SPOT and Landsat TM satellite data have also been used in production of forest inventories. The most frequently used method has been developed by the Department of Remote Sensing within the Faculty of Forestry at the Swedish University of Agriculture (Hagner, 1990). This method is based on segmentation in the satellite data in which homogenous segments of forest units are created. This information, in combination with sample plot measurements, is then used for estimating selected forest variables for the defined forest units.

The Forest Research Institute in Finland at Metla has developed a Multi Source Forest Inventory (MRFI) method to increase the accuracy of the National Forest Inventory in the country (Tompo, 1997). The method is based on a combination of the following information sources: Landsat TM data, digital land cover information, digital terrain models, and sample plot information from the National Forest Inventory.

During 1999, the Swedish Forestry Board will support all of the 97 forest districts in the country with SPOT satellite data. This data will be used in applications such as:

- Monitoring of clearcuts.
- Extension service to the forest sector.
- Inventories and management planning.

Forest companies in Sweden and Finland have started to use satellite data in their routines for timber procurement. In one of the methods developed by Älvsbyhus, different digital information sources such as topographic maps, property registers, OSI forest inventory data, and satellite data are combined in a GIS. The method enables the individual purchasing the timber to identify stands and forest holdings desired in the purchase process.

The Swedish Forest Company AssiDomän is using Landsat and SPOT satellite data for revision of forest inventories for some of its forest districts. Clearcuts, forest roads, and objects requiring precommercial thinning are identified and monitored in the revision process (Walter, 1998).