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Aerospace Methods and Technologies for Monitoring Oil and Gas Areas and Facilities

V. G. Bondur

Institute for Scientific Research of Aerospace Monitoring AEROCOSMOS, Ministry of Education and Science of the Russian Federation and Russian Academy of Sciences, Moscow, Russia

e-mail: vgbondur@aerocosmos.info

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Abstract—The urgency and specific features of the application of the up-to-date aerospace methods and technologies in order to monitor different oil and gas facilities; study subsurface geology of oil and gas areas; search for oil and gas deposits (particularly in Arctic regions); control oil, gas, and product pipelines; and estimate the environmental conditions in the areas of hydrocarbon production and transportation on land and on the sea are justified and analyzed. The problems in the oil and gas industry which can be solved using aerospace data are systematized. The principles of organization of aerospace monitoring and the physical bases of remote sensing methods for solving different problems in the oil and gas industry are considered. The application of aerospace methods and technologies in order to monitor the environmental conditions in the oil and gas production areas, monitor pipelines, detect pollution of the marine environment with oil products (particularly, after the accident on the oil platform in the Gulf of Mexico in 2010), and control the ice conditions in the Arctic oil and gas areas is illustrated.

Keywords: aerospace monitoring, remote sensing, oil and gas areas, oil and gas facilities, environmental protection.

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INTRODUCTION

Oil and gas are the most important components of worldwide power engineering. They satisfy the energy needs of mankind by more than a third. At present, the contributions of oil and gas to the total consumption of natural energy resources are 40 and 23%, respectively. At the same time, the contributions of natural gas and oil to the balance of energy sources in Russia are 52 and 23%, respectively (Laverov, 2006). In our country, the natural resources of hydrocarbons are enormous. Therefore, the oil and gas industry plays the key role in the economy of present-day Russia. The state balance of hydrocarbon resources includes more than 2500 deposits of oil and natural gas. These deposits differ in their resources, stages of development, and location (Kontorovich and Korzhubaev, 2002). The explored resources are mainly located in Western and Eastern Siberia and on the sea shelf of Sakhalin and the Barents and Kara seas. Potential oil and gas provinces occupy wide areas and differ sharply in the extent of maturation of reserves and predicted resources (Mazur and Lobov, 2004). To obtain new information about the subsurface geology of oil and gas areas, evaluate the presence of oil and gas, and organize information support for prospecting for hydrocarbon deposits, it is necessary to use innovative methods and technologies, including aerospace methods, which are among the most effective ones.

Transport systems (oil, gas, and product pipelines and tankers used to transport oil, oil products, and condensed gas) play an important role in activities of the Russian oil and gas complex. More than 1 000 000 km of main, field, and distributing oil, gas, and product pipelines are maintained in our country. The pipeline system covers 35% of a vast area occupied by almost 60% of the Russian population. On average, about 55 accidents take place every year just on main pipelines (*Russia's Security...*, 2002; Mazur and Ivantsov, 2004). In connection with this and with increasing pipeline control and safety requirements, it has become necessary to develop and implement new methods and tools for diagnosing these facilities. To solve this problem, it is promising to use aerospace methods and technologies since they have advantages and unique features that make it possible to reveal, first of all, such pipeline damage as wormholes and cracks, which do not affect the transportation process and cannot be detected by parametric methods and in-pipe monitoring systems.

Permanent losses caused by leakages, spills, breaks, accidents, and other sources usually take place at enterprises engaged in producing, storing, transporting, distributing, and processing oil, gas, and oil products, which results in environmental pollution. In this case, oil and oil products are among the most hazardous pollutants because they are mixtures of organic compounds including a large amount of chemically active substances, which change the composition of objects in the environment, transforming natural components into toxic forms.

Many accidents take place in areas of oil and gas production and transportation. The accident on the British Petroleum oil platform in the Gulf of Mexico in April 2010 is one of the last famous examples. Modern aerospace methods and tools can successfully be used to monitor environmental conditions in surface and sea areas where oil and gas enterprises are located.

It is necessary to use the latest advances in science and the corresponding information support in order to rationally use hydrocarbon natural resources; control safety at the facilities of production, storage, transportation, and distribution of oil, oil products, and gas; and increase the functional effectiveness of oil and gas enterprises. Extensive application of modern remote sensing (RS) aerospace methods and technologies, new aerospace data processing methods, and geoinformation technologies is one of the effective methods for solving this problem.

The present work is devoted to considering these problems.

SPECIFIC FEATURES OF AEROSPACE METHODS AND TECHNOLOGIES

Remote sensing of the Earth (RSE) is one of the most important and thriving types of space activities, which is most sensitive to innovations. This type of activity is most promising and already makes a great contribution to the economy of developed countries. The characteristic feature of this activity consists in high rates of development and a rapid achievement of practically significant results. This sector of space activities is based on using high knowledge-extensive technologies and the last advances in fundamental and applied science.

Space information is used in many fields, first of all, in order to prevent and mitigate consequences of natural disasters and technogenic accidents, study and rationally use natural resources, and protect the environment for the purpose of power engineering, urban planning, transport complex, meteorology and climatology, forestry and farming, mapping, etc. (Bondur et al., 2009b). This information should naturally be widely used for the benefit of oil and gas industry.

Aerospace methods and technologies will more effectively be used in different fields of human activity (including oil and gas industry), taking into account the main tendencies in the development of RSE systems related to an increased number of high- and ultrahigh-resolution (less than 0.4–1 m) satellites (including all-weather radar spacecraft), progressively wider utilization of small satellite clusters, creation of complex multisatellite space monitoring systems, rejection of inefficient photographic space equipment, and broad international cooperation in the RSE field.

The main advances of the space monitoring methods and systems are as follows: a considerable field of view, the possibility of operating in any regions difficult to access, obtaining almost any-scale data with different spatial and time resolutions, a wide range of registered parameters, a high reliability and efficiency of data acquisition, the possibility of repeatedly observing studied regions and operating at a partial or complete absence of a topographic base, and relatively inexpensive data acquisition (especially when wide areas are studied) (Bondur, 2004; Bondur et al., 2009a).

Aircraft monitoring tools occupy their own niche in monitoring oil and gas facilities when it is necessary to obtain more detailed information on a more local scale. Their effectiveness of application increases substantially when they are combined with space methods.

It is necessary to apply aerospace methods and technologies in the Russian oil and gas industry because

(i) oil an gas areas are wide;

(ii) hydrocarbon transportation pipelines are extensive;

(iii) most areas where hydrocarbons are produced and transported on land and in offshore strips are hardly accessible;

(iv) weather conditions are unfavorable;

(v) the possibilities of solving many various problems in the oil and gas industry are wide and progressively increasing.

Different RS methods, including those described in (Savin and Bondur, 2000; Bondur, 1995, 2004; Bondur and Zubkov, 2001; Khrenov, 2003; *Aerometody...,* 1971; Kharitonov et al., 2004; *Geoekologicheskoe...*, 1999; Volker et al., 1996), are used to perform aerospace monitoring of oil and gas facilities: the methods based on registering electromagnetic field characteristics (first of all, optoelectronic scanner ones); thermal vision methods; IR and UHF radiometry; hyperspectral methods; lidar methods; synthesized aperture (SARs) and side looking (SLRs) radars; magnetometry; gravimetry; and passive methods based on registering particle fluxes (gamma spectrometry).

The effectiveness of aerospace monitoring of oil and gas facilities can be increased by using such new RS methods as remote spatial–frequency spectrometry, multifrequency radiotomography and ULF radiometry, multifrequency radiowave recording, radio interferometry, bistatic radiolocation, Fourier spectrometry, laser fluorovision, satellite navigation methods, satellite altimetry, and active methods based on registering fluxes of elementary particles and using various aerospace and subsatellite (including geophysical) data. This effectiveness can also be increased by developing methods and technologies for processing and storing various aerospace data and up-to-date geoinformation support (Bondur, 2004; Savin and Bondur, 2000; Bondur et al., 2009a; Trifonov, 2010; Lopatin, 1996; Kharitonov et al., 2004).

OIL AND GAS INDUSTRY PROBLEMS SOLVABLE USING AEROSPACE METHODS AND TECHNOLOGIES

Areas where new oil and gas deposits will be developed, including such areas in Arctic regions; areas where hydrocarbons are produced and transported on land and on the sea; oil, gas, and product pipelines; oil processing complexes; storage facilities of raw materials and products; water and surface vehicles used to transport oil, oil products, and condensed gas; etc., are the main oil and gas facilities to be monitored.

At present, the following problems can first of all be solved using aerospace methods and technologies for the benefit of the oil and gas industry:

(i) basic scientific research of hydrocarbon formation and migration based on aerospace data;

(ii) studying the subsurface geology of oil and gas areas, including examining the lineament network and deep tectonics and ring structures; tectonic zoning of these areas based on space data in order to support surveying aimed at detecting new oil and gas deposits and estimating the potential of exisiting ones;

(iii) monitoring the current conditions of oil, gas, and product pipelines for leaks and violations of technical conditions;

(iv) determining potentially dangerous sections of pipelines, including variations in floodplains, basins, and swamped areas as a result of the dynamics of soil cryogenic and hydrophysical properties; estimating the soil freezing dynamics and its effect on pipelines; and determining the most favorable conditions for laying new pipelines;

(v) monitoring hazardous natural and technogenic processes when hydrocarbons are produced and transported, including such processes as earthquakes, mudflows, avalanches, landslides, tsunami, and hurricanes, based on aerospace data;

(vi) remote monitoring of ice conditions in Arctic regions, including areas with drilling platforms and Northern Sea Route;

(vii) online space monitoring of fires in buffer zones of main pipelines and other oil and gas facilities;

(viii) environmental monitoring of areas where hydrocarbons are produced, transported, and processed on land and on the sea in order to assess the consequences and mitigate the risks of operation of oil and gas enterprises, namely, identification of petrochemical pollution of soil, vegetation, and snow cover within drilling sites and oil pumping stations; sea platforms, oil storage facilities, and zones where oil carriers are loaded and unloaded; subsurface and subsea pipelines; determining lake blooming as a result of income of mineral and organic suspensions; etc;

(ix) controlling rates and estimating effectiveness of land and polluted area rehabilitation based on aerospace data;

(x) ecological certification of oil and gas facilities using aerospace data;

(xi) determining the location of pipelines, structures, and other oil and gas facilities and formation of their cadasters based on aerospace data;

(xii) creation of digital maps, 3D models of localities, and different-purpose GIS for oil and gas areas using aerospace data;

(xiii) remote monitoring of illegal tapping of main oil and product pipelines;

(xiv) identification of illegal economic and construction activities and the appearance of technogenic facilities in the zones allotted for oil and gas facilities based on aerospace data;

(xv) remote monitoring of areas where new oil and gas facilities are constructed;

(xvi) space monitoring of the areas where accompanying gas is burned and control of flare unit functioning;

(xvii) information support of long-range planning, control of oil and gas enterprise activity, and elimination of accidents at these enterprises using aerospace data.

The spectrum of these problems can be extended with the development of methods, technologies, and tools for RS and processing the data obtained.

ORGANIZATION PRINCIPLES OF AEROSPACE MONITORING FOR THE PURPOSE OF THE OIL AND GAS INDUSTRY

When aerospace monitoring is organized for the purpose of the oil and gas industry, it is necessary to use the principles typical of complex information systems (Bondur, 1995; Savin and Bondur, 2000). Different spacecraft and airborne vehicles (aircraft, helicopters, drones, airships) with numerous passive and active RS equipment operating in different ranges of the electromagnetic wave spectrum (from UV to radio waves) as well as geophysical equipment, communication tools, ground receivers of satellite data, situation and information–analytical centers, software and hardware tools for long-term storage and presentation of aerospace data, and corresponding geoinformation support should be used to perform aerospace monitoring of oil and gas facilities.

Figure 1 presents the scheme of aerospace monitoring of oil and gas areas and facilities, and Fig. 2 gives the schematic diagram of information product formation during such monitoring.

Oil and gas facilities can be monitored using

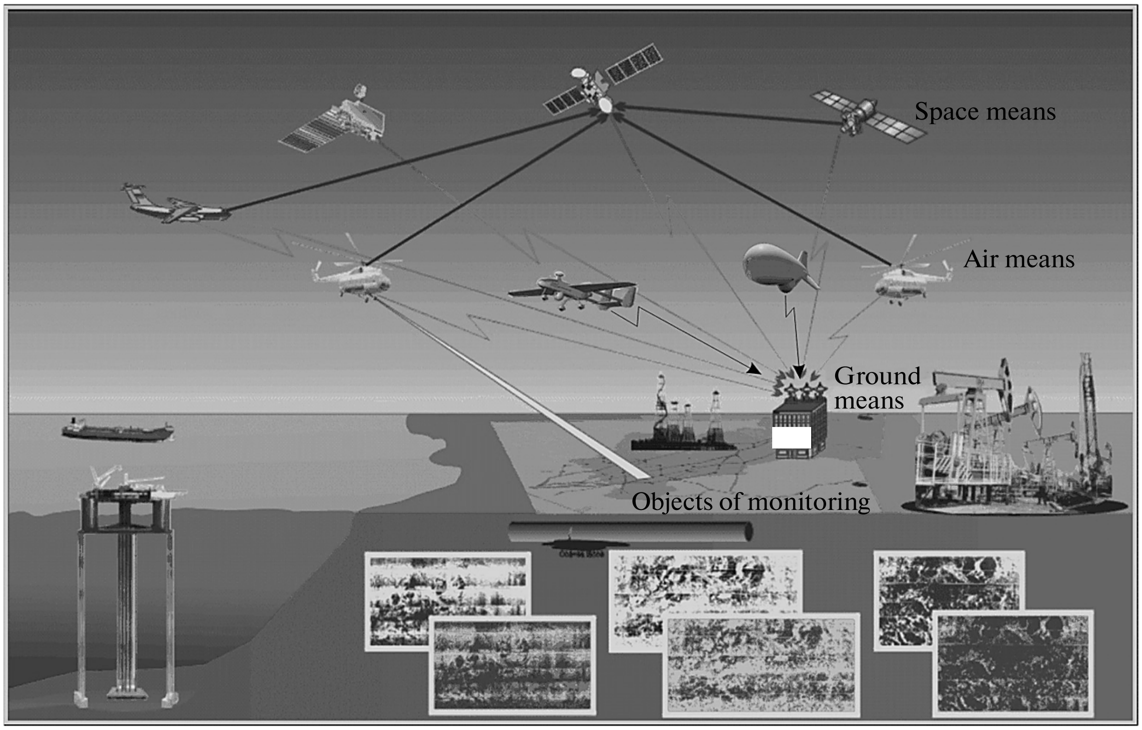

Fig. 1. Scheme of aerospace monitoring of oil and gas areas and facilities.

(i) satellites with optical equipment operating in the UF, visible, and IR spectral ranges and having an ultrahigh and high resolution (0.4–4.0 m); multispectral equipment with a medium (5.0–90 m) and low (100 m–1 km) resolution (survey devices); and hyperspectral equipment;

(ii) radar satellites equipped with high- (1.0–8.0 m), medium- (12.5–25 m), and low-resolution (100–600 m) SARs;

(iii) satellites for magnetic and gravitational surveys;

(iv) meteorological satellites;

(v) satellite navigation equipment;

(vi) manned long-term orbital stations;

(vii) airborne vehicles (aircraft, helicopters, delta planes, drones, and airships) equipped with digital optical cameras, optoelectronic scanners, hyperspectrometers, radiothermal vision sets, IR radiometers, lidars, SARs, microwave radiometers, gamma survey equipment, and other devices;

(viii) communications and data transmission facilities;

(ix) ground situation and information–analytical centers;

(x) software and hardware for processing data, formation of databases, presentation of spatially organized data as GIS in order to solve a wide spectrum of oil and gas problems.

Initial data (aerospace images, other RS data, and geophysical data) are formed when aerospace monitoring of oil and gas areas and facilities is performed. When air-borne monitoring equipment is used, online data processing can be performed aboard aircraft, and its results can be transmitted online to consumers or to ground data processing facilities (see Fig. 2).

Data from different satellites can be received online by ground antenna systems or through FTP servers or can be inserted from magnetic carriers. The schematic organization of data recording, processing, and storage during space monitoring is presented in Fig. 3.

During monitoring, aerospace and accompanying data are subjected to preliminary and detailed thematic processing. The results are used to form intermediate information products, thematic maps, and GIS of different thematic orientation, which form the basis for recommendations for taking managerial decisions. Data obtained at any stage of information product formation can be transferred to main or regional situational or information–analytical centers of consumers (see Fig. 2).

PHYSICAL BASES OF AEROSPACE MONITORING OF OIL AND GAS AREAS AND FACILITIES

Environmental Monitoring of Hydrocarbon Production and Transportation Areas

When numerous problems of the oil and gas industry are solved, RS of different facilities is performed on land and on the sea. Oil and gas components escape in

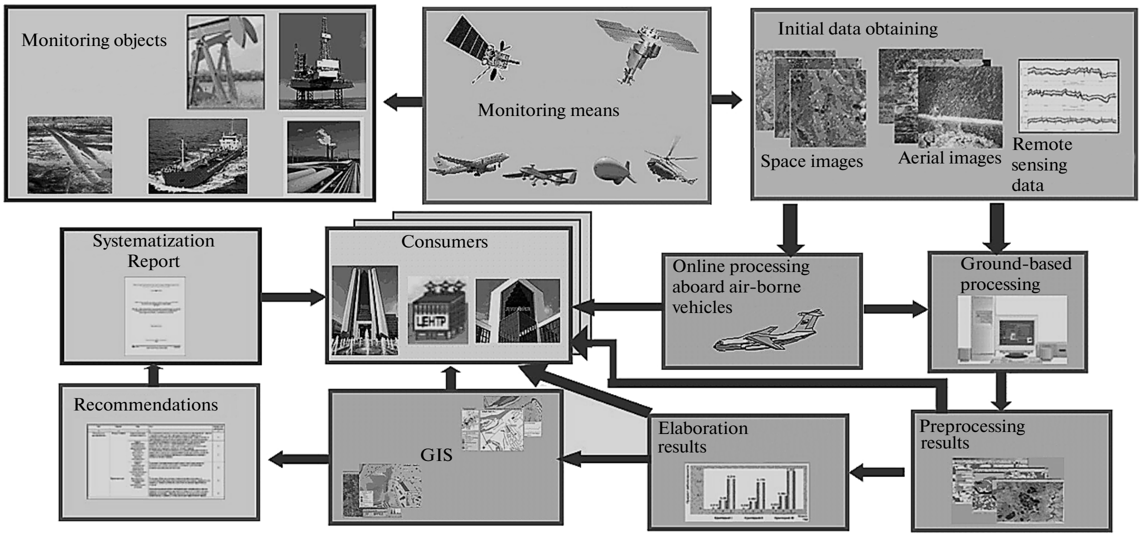

Fig. 2. Schematic diagram of formation of information products during aerospace monitoring of oil and gas areas and facilities.

emergency situations at these facilities, as a result of which the environment becomes polluted. Different changes on and below the surface of the Earth and the water are registered in this case.

Earth's surface. Detection of oil and gas components on and below the Earth's surface is based on the following main physical effects which manifest themselves in a change in the characteristics of the electromagnetic radiation registered by aerospace equipment (Bondur, 1995, 2000, 2004; Bondur and Grebenyuk, 2001; Mezheris, 1987; Glushkov et al., 1994; Deinan et al., 1994; Khrenov, 2003):

(i) origination of thermal contrasts in pipeline accident areas and the appearance of pollutants on the surface registered by IR and thermal equipment;

(ii) appearance of brightness contrasts between anomalous areas and the background in different electromagnetic spectrum regions owing to a difference in the spectral brightness coefficients, which are registered by a multispectral or hyperspectral aerospace equipment;

(iii) narrowing of the spectrum of radar signals reflected from the pollution of the Earth's surface as compared to the background spectrum or a change in the signal correlation characteristics in the background and polluted areas registered by radar;

(iv) a change in soil permittivity in the zones where oil, gas, and product pipelines are broken owing to the effect of chemically active components on soil registered by multifrequency radar;

(v) a change in the fluorescence spectra in anomalous areas (in zones where oil and oil products appear) as compared to the background, registered by fluorescence lidars.

The difference in radiation temperatures of an object and background depending on their physical temperatures and emission coefficients is one of the important parameters responsible for monitoring oil and gas facilities using thermal vision, IR, or UHF radiometric instruments.

This is due to the following circumstances. In the case of leaks from product or gas pipelines, the thermal contrast is caused by the Joule–Thomson effect, which consists in a decrease in temperature due to the transition of the liquid phase into light gaseous fractions of hydrocarbons. In addition, the oil temperature in a pipeline is as a rule higher than the soil temperature at the same depth. Therefore, when oil escapes in an underground channel with a relatively small cross section, its temperature decreases with increasing distance from a damaged pipeline as a result of a thermal exchange with the environment. Consequently, a remote measurement of the soil temperature makes it possible to reveal leaks and localize defects in oil pipelines (*Geoekologicheskoe*..., 1999).

When oil, oil products, or gaseous components related to leaks from pipelines affect the grass cover and soil, the brightness characteristics in different spectral ranges $\Delta\lambda_i$ change owing to variations in soil and vegetation spectral reflectivity that can be registered by multispectral and hyperspectral aerospace instruments. In addition, the NDVI and NCHVI vegetation indices, which are adequately registered using the data obtained by multispectral RSE optical equipment and by jointly used optical and radar instruments (Bondur and Chimitdorzhiev, 2008), change in these cases.

In the areas polluted by oil or oil processing products (gasoline, kerosene, lubricants), the specific effective scattering surface (SESS) changes (decreases), as a result of which the radar output signal level changes (decreases). This makes it possible to remotely detect such pollution.

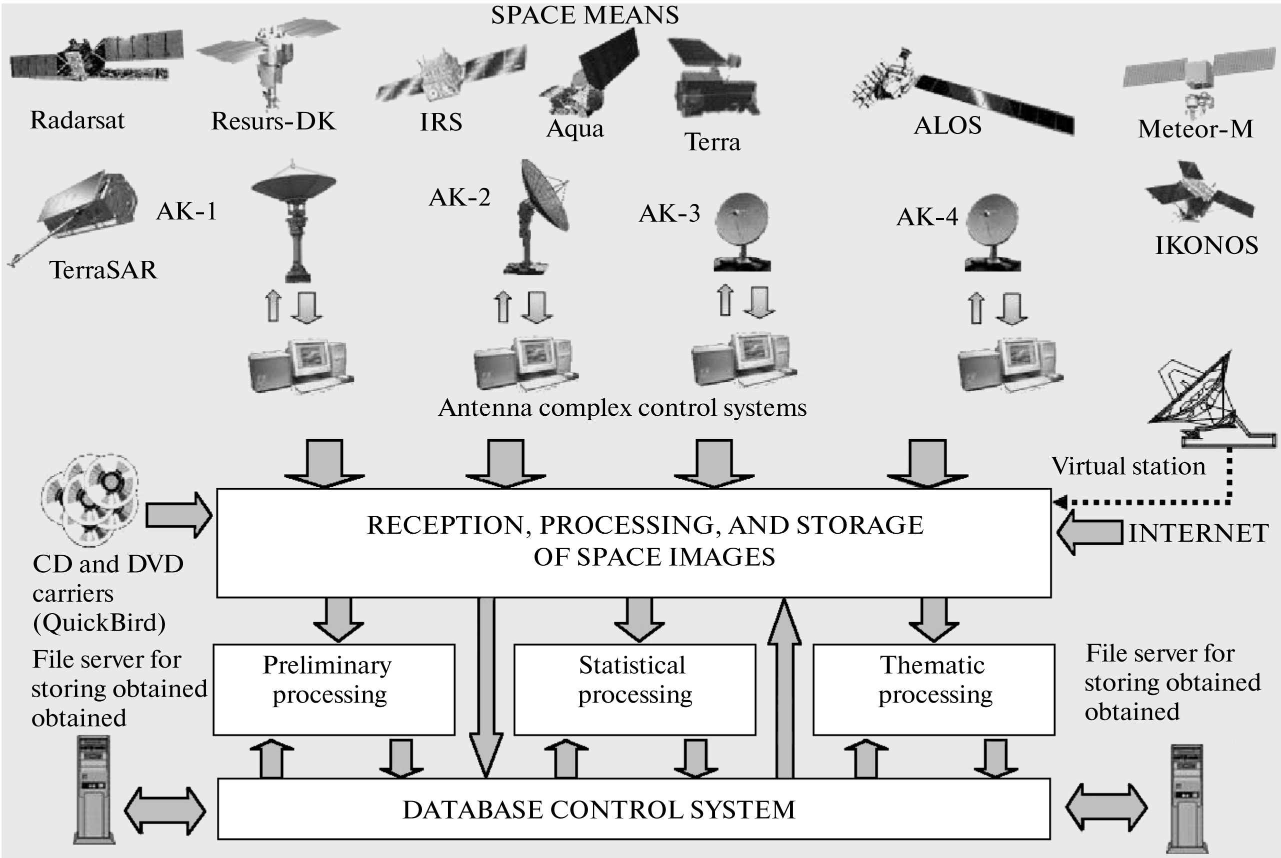

Fig. 3. Organization of data acquisition, processing, and storage during aerospace monitoring.

A local gas spot is formed when a subsurface gas pipeline is broken. This spot is concentrated in a certain zone near a broken pipeline and changes the permittivity of the environment, which (as well as a local change in temperature) is an important indication of gas pollution of the environment detected by RSE.

Laser fluorescence spectroscopy (Mezheris, 1987; Bondur and Zubkov, 2001; Deidan et al., 1994) is one of the most effective methods for diagnosing the conditions of the environment in the areas where oil and gas is produced and transported. Crude oils at different deposits, as well as oil fractions (gasoline, black oil, etc.), differ in the percentage of methane, naphthene, and benzene hydrocarbons. Since each hydrocarbon component has its own individual fluorescence characteristics, an oil product can be determined on the basis of its fluorescence spectrum. Fluorescence of any product is characterized by the following main parameters that can be used as corresponding disclosing indications (Mezheris, 1987; Glushkov et al., 1994):

(i) the spectral distribution of fluorescence intensity $S_i^{rel} = S_i/S_{max} = f(\lambda_i)$, i.e., the spectral form or position of the maximum;

(ii) the fluorescence effectiveness $\psi_i = \varphi_i k_0$ at wavelength λ_i;

(iii) the spectral distribution of time constants $\tau_i = f(\lambda_i)$, i.e., the damping time spectrum.

In addition, Raman lines, which are independent of oil film thickness and are related to oil product individuality in contrast to the first three characteristics (Deidan et al., 1994), can be used in remote identification of oil products.

A complex utilization of the spectral and time fluorescence characteristics makes it possible to identify oil products not only on the basis of groups (crude oil, light fractions, heavy residual fractions) but also on types (different lubricants, diesel fuel oil, etc.) and possibly individual oil product grades.

Aquatic environment. As for the Earth's surface, the physical principles of remote monitoring of the aquatic environment in the areas where oil is produced and transported on the sea are based on several fundamental phenomena.

First, in the presence of pollutants of the liquid fraction or gas components ascending toward the surface (e.g., when oil and gas pipelines are broken), the spectral composition of the sea wave changes owing to "smoothing" of the fine structural components of this wave (Bondur, 1987, 1995, 2004). Such a change can be registered using a spatial spectral analysis of optical images by the method of remote spatial–frequency spectrometry and radar methods (Bondur, 1987, 1995, 2000, 2004; Bondur and Grebenyuk, 2001).

The radar systems (SLR, SAR) sensing the surface at low angles ($\theta \approx 10°–40°$ is the beam grazing angle) use the effect of Bragg signal reflection, when re-emission of signals by the sea surface toward a receiving antenna mainly takes place at a resonant wavelength (Bass et al., 1968; Elachi and Brown, 1977)

$$\kappa = 2 \cdot \kappa_0 \cdot \cos\theta,$$

where $\kappa = 2 \cdot \pi / \Lambda_{SW}$, $\kappa_0 = 2 \cdot \pi / \lambda_0$, Λ_{SW} is the sea wavelength, and λ_0 is the radar wavelength.

A radar itself registers a decrease in the level of a signal reflected from the polluted surface by light fractions, and areas with a clearly defined negative contrast (dark bands), where the reflected signal level is lower than the background signal level, will be observed on radar images (RIs) of the water surface. Such a pattern will be observed when sea waves are higher than 0.5–1 points and angles of surface vision are >35° (Bondur, 2004). When waves are weak or it is calm (0–0.5 points), positive contrast anomalies relative to the receiver noise level will be observed in polluted areas especially in the presence of the bubble gas component of the pollution (Bondur, 2004).

Second, the presence of admixtures with properties sharply different from those of pure water results in a change in permittivity (the relative permittivity of pure water and gasoline is known to be $\varepsilon \approx 80$ and $\varepsilon \approx 2–4$) and in the level of a radio signal reflected from polluted water or sea surface (contrasts are ~2–8 dB).

Third, the origination of oil and gas polluting components in water can result in the appearance of density depth gradients ($\Delta\rho/\Delta_h$), which can theoretically cause internal waves. Their interaction with surface waves results in the appearance of flat bands on the sea surface, which can be registered during a spatial spectral analysis of optical or radar images (Bondur, 1987, 2000, 2004).

Fourth, the presence of currents in the zone of pollutants that entered the seawater (including the situation where surrounding water layers are captured) can form the physical basis for their detection using coherent radar systems; in particular, SARs can be used to register the Doppler frequency shift toward the SAR antenna pattern or in the opposite direction (Bondur, 2004).

Fifth, water temperature changes in the area of oil pollutions. A change in the physical temperature and, correspondingly, surface radio-brightness temperature is most typical of gas components. These effects are registered by thermal-vision and radiothermal instruments (Bondur, 1995, 2000, 2004).

Sixth, the spectral brightness coefficients in different spectral ranges, which can be registered by multispectral and hyperspectral optical instruments, change in the areas polluted by oil (Bondur, 2004, Bondur and Zubkov, 2005; Bondur et al., 2006; Volker et al., 1996).

Seventh, fluorescence spectra change when dissolved emulsified and dispersed oil fractions appear in water. In this case, signals of water fluorescence are characterized by a higher intensity as compared to background signals. The Raman scattering (RS) line of water is also suppressed in this case. These effects can be detected by fluorescence lidars (Mezheris, 1987; Bondur, 2004; Bondur and Zubkov, 2001; Lutomirski, 1994).

Thus, the appearance of contrast related to water pollution by oil, oil products, and gas components can have the following physical causes: changes in the sea wave spectral composition due to the suppression of HF gravitational–capillary components, temperature of the environment, spectral brightness coefficients, fluorescence spectra, permittivity, Doppler frequency shift of radar signals owing to the appearance of currents, etc., which are registered on optical and radar images by hyperspectrometers, thermal vision, and UHF radiometers as well as by fluorescence lidars.

Use of Aerospace Data in Order to Search and Explore for Hydrocarbons

The possibilities of using aerospace methods in order to search and explore for oil and gas deposits are related to the fact that vertical migration of stratal fluids (including hydrocarbonaceous ones) are most favorable in zones of faults and increased fracturing, which manifest themselves as lineaments and ring structures (Trifonov, 2010). This can be registered on multispectral and hyperspectral space images. The formation of lineaments registered on such images is related to tectonic, rotational, and fluid-geodynamic mechanisms. In this case, migration of hydrocarbonaceous fluids and heat and mass transfer from deep layers and the Earth's surface cause a change in the soil and vegetation spectral characteristics and in the transparency of the near-Earth air. The integral effect of these factors results in anomalies detected on space images caused by a change in the stressed and strained state of the Earth's core and fluid-geodynamic processes (Bondur and Zverev, 2007).

Geological singularities in the form of the systems of direct and arc-shaped lineaments and oval–ring formations are detected on space images during a structural–morphological analysis. Structural–morphological singularities of the lineament network registered on space images reflect specific features in the depth structure of the lithosphere. These singularities are informative indications used to evaluate promising oil and gas structures and their hydrocarbonaceous potential.

Monitoring a change in the stressed and strain state of the environment by registering an increased expressiveness of lineament systems on space images makes it possible to register geodynamic precursors of seismic events in oil and gas areas hazardous to oil and gas facilities (Bondur and Zverev, 2005a, b, 2007).

The methods of computer lineament analysis using different programs for processing space images, e.g., LESSA, ALINA, and other program packages (Zlatopolsky, 1997; Shchepin et al., 2007), are used to automatically detect lineaments and oval–ring formations. We should also note that space RIs can also be used to study lineament systems.

Specific isometric topographic features in the form of weak neotectonic uplifts also originate in the areas with local oil and gas structures. Zones of tectonic uplifts are most favorable for the location of oil and gas traps (Trifonov, 2010). These structures can be revealed on optical and radar images on the basis of morphological, hypsometric, and morphometric indications. Such neotectonic uplifts can also be registered using the methods of satellite altimetry and radio interferometry. Such satellite navigation systems as GPS and GLONASS can be used to register and analyze structural singularities and specific topographic features in oil and gas areas.

Hydrocarbonaceous deposits in traps, which manifest themselves as structural uplifts, result in an increased temperature of the Earth's surface. This is caused by the activity of microorganisms within deposits, and an increased fluid permeability related to the newest activation of fractures and, partially, to an isostatic uplift owing to the fact that deposits are lighter than the host rock results in an increased soil moisture content (Lyal'ko et al., 2006; Trifonov, 2010). These effects can be registered by RS equipment in the IR and microwave spectral ranges.

Large geological structures are also reflected in the radioactive field and, specifically, in the gamma radiation intensity level depending on morphological features of these structures. The physical mechanisms by which the surface gamma field is related to the depth structure and, consequently, to the manifestation of oil and gas structures are related to the fact that geological structures that develop during sedimentation are accompanied by the differentiation of a physical material and by a change in the physical parameters of sedimentary rock (porosity, density, fracturing, etc.), which is reflected in the distribution of radioactive elements (*Aerometody...*, 1971).

The possibilities of remotely searching for oil and gas deposits on the sea shelf are related to the fact that hydrocarbonate traps are as a rule confined to deep horizons of the sedimentary mantle and are mapped as different structural forms in bottom landscapes, in a water body, and on its surface (Lyal'ko, 2006). Aerospace methods for determining bottom topography based on the effects on the surface and in the subsurface sea layer described in (Bondur, 2004; Bondur and Grebenyuk, 2000) can be used to study deep-seated faults, decompaction zones, and local structures. Such structures can be detected using special methods for processing optical and radar images of the sea surface (including the method of remote spatial–frequency spectrometry, multifrequency radio-wave recording, etc., described, e.g., in (Bondur, 1987, 1995, 2004; Bondur and Grebenyuk, 2001)).

A structural–geomorphological analysis is performed, lineament zones are classified, and the potential of studied shelf areas for the presence of hydrocarbons is determined on the basis of an analysis of the schemes of lineaments and oval–ring formations, spectral density distributions, and received radio-signal characteristics (Lyal'ko, 2006).

The remote methods based on the registration of magnetic and gravitational field anomalies (Lopatin, 1996) can also be used to reveal the presence of hydrocarbons on land and on the sea shelf. The physical mechanisms responsible for the possibilities of using such methods are related to the fact that the foundation fault tectonics as well as uplifts and troughs of the Earth's crust reflecting shear zones manifest themselves in the primary registered gravitational and magnetic fields and in derivatives, e.g., field gradients. In this case, negative and positive anomalies of the gravitational and magnetic field are observed in uplift and trough zones. The oil and gas content enhances these effects, which makes it possible to evaluate the hydrocarbonate potential by registering magnetic and gravitational field anomalies (Lopatin, 2006; Trifonov, 2010).

Such fields can be registered from MAGSAT, GEOS, and CHAMP satellites (Kharitonov et al., 2004).

SOME EXAMPLES OF USING SPACE METHODS IN ORDER TO MONITOR OIL AND GAS FACILITIES

Monitoring Ecological Conditions in Oil Production Areas

Figure 4 (on the right, color inserts) shows the RGB-synthesized image obtained from the QuickBird satellite for an oil production area (Pionernyi camp, Tomsk oblast). The landscape features of the studied area, which are presented on the color scale (see Fig. 4), were identified using the NDVI and TCHVI vegetation indices and classification by the maximum likelihood method as a result of processing this image.

Figure 5 (color inserts) illustrates processing of the space image fragment (top left) obtained from the QuickBird satellite presented in Fig. 4.

The color-coded image of this fragment, compiled in false color in order to identify anthropogenic impact areas, is presented at the bottom left. A yellow square marks the enlarged area presented in Fig. 5 (on the right).

Figure 5 (top right) shows an enlarged fragment of the color-coded image reflecting anthropogenic changes in the landscape near Pionernyi camp. The

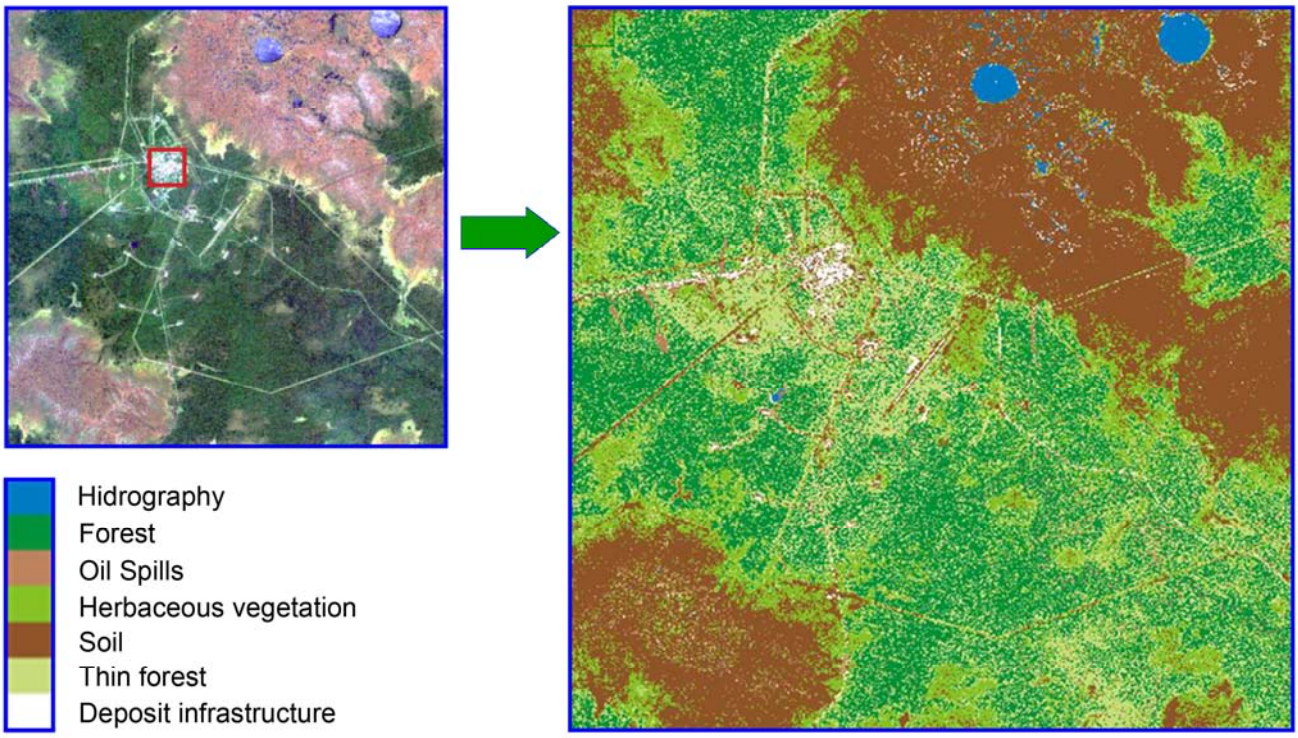

Fig. 4. Detection of landscape singularities based on the results of classification performed using the maximum likelihood method.

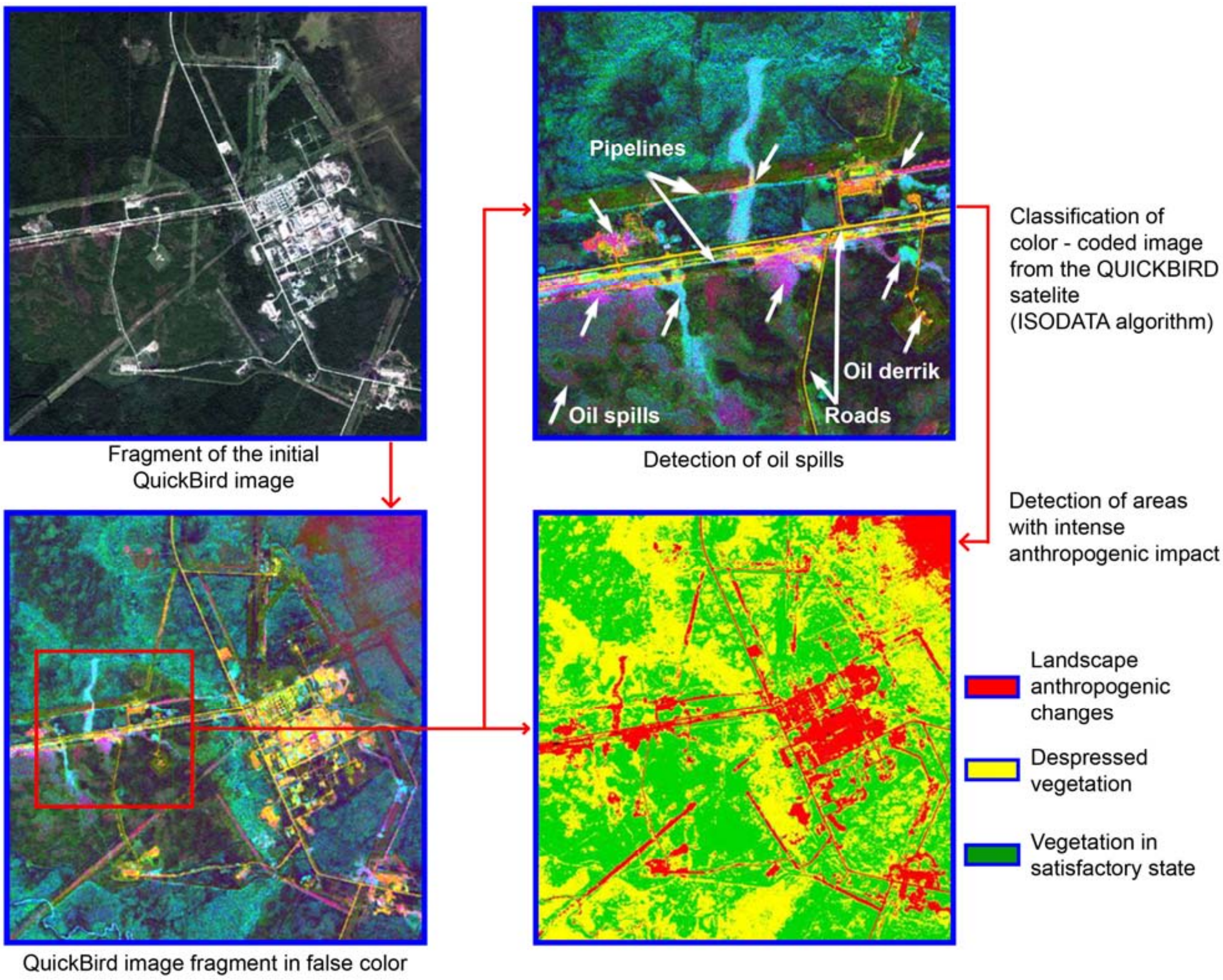

Fig. 5. Detection of areas subjected to intense anthropogenic impact.

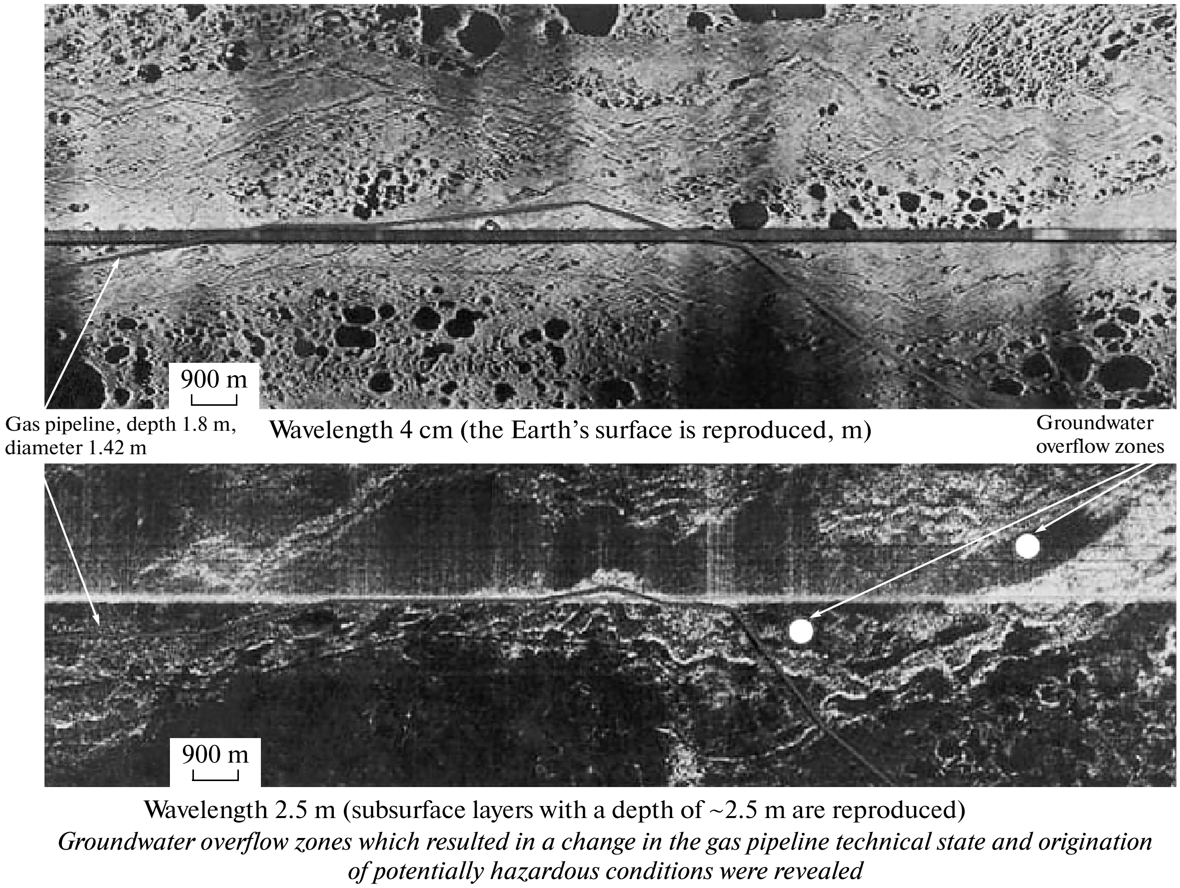

Fig. 7. Multifrequency RIs in the Novyi Urengoi–Surgut gas pipeline segment.

areas polluted by different oil products are colored pink, violet, and light blue in this figure; infrastructure facilities (roads, pipelines, oil derrick) are colored yellow.

An uncontrolled classification of this fragment by the method of averages with a forced determination of three classes is presented at the bottom right of Fig. 5. The classification results can be interpreted as areas corresponding to different degrees of impact on the environment. Anthropogenic changes in the landscape caused by strong pollution, road and pipeline laying, construction of infrastructure facilities, deforestation, etc., are colored red. Yellow corresponds to the areas with depressed vegetation owing to the effect of the oil production complex; green corresponds to the areas with satisfactory environmental conditions.

An analysis of the results achieved based on space data indicates that the anthropogenic impact on the environment in the oil production area is extremely high. Intense oil and oil product spills, degradation of vegetation and soil covers, and other natural landscape disturbances caused by the effect of leaks and intense economic activities in the studied area were revealed.

Multifrequency Radar Monitoring of Pipelines

The method of radiotomography based on multifrequency radio sensing is effectively used to monitor oil, gas, and oil product pipelines. In this case, the surface is reproduced in the centimeter range on RIs, and the possibility of tracing below the surface and controlling the pipeline state at the depth of laying is shown in the meter range (Savin and Bondur, 2000).

The operating principle of an aviation two-frequency radar is illustrated in Fig. 6 (color inserts). Figure 6 presents the survey scheme (Fig. 6a), RI fragments obtained in the Nizhnevartovsk region at wavelengths of $\lambda_1 = 4$ cm (Fig. 6b, top) and $\lambda_2 = 2.5$ m (Fig. 6c, top), and a difference image (Fig. 6d, top). The bottom fragments of Figs. 6b–6d illustrate the classification and color coding based on the brightness of the upper initial RIs (in the centimeter and meter ranges) and a difference analysis using the ISODATA cluster algorithm. Subsurface oil spills were revealed on processed difference RI (see Fig. 6d, bottom).

Figure 7 presents examples of a two-frequency radar aircraft survey of segments along the route of the Novyi Urengoi–Surgut gas pipeline; Fig. 8 presents such examples of the Urengoi–Surgut–Chelyabinsk

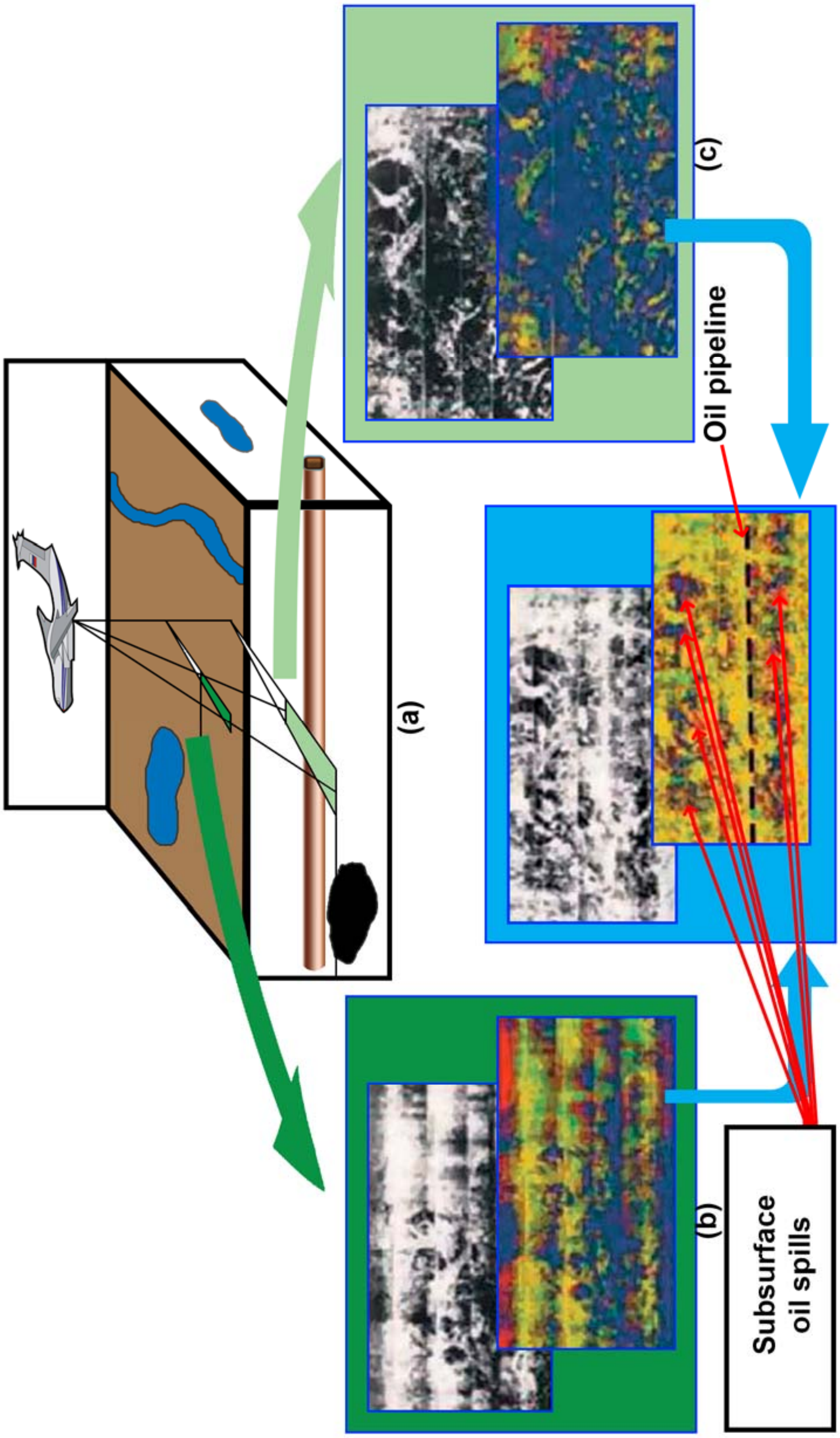

Fig. 6. Multifrequency radar survey for controlling the pipeline state.

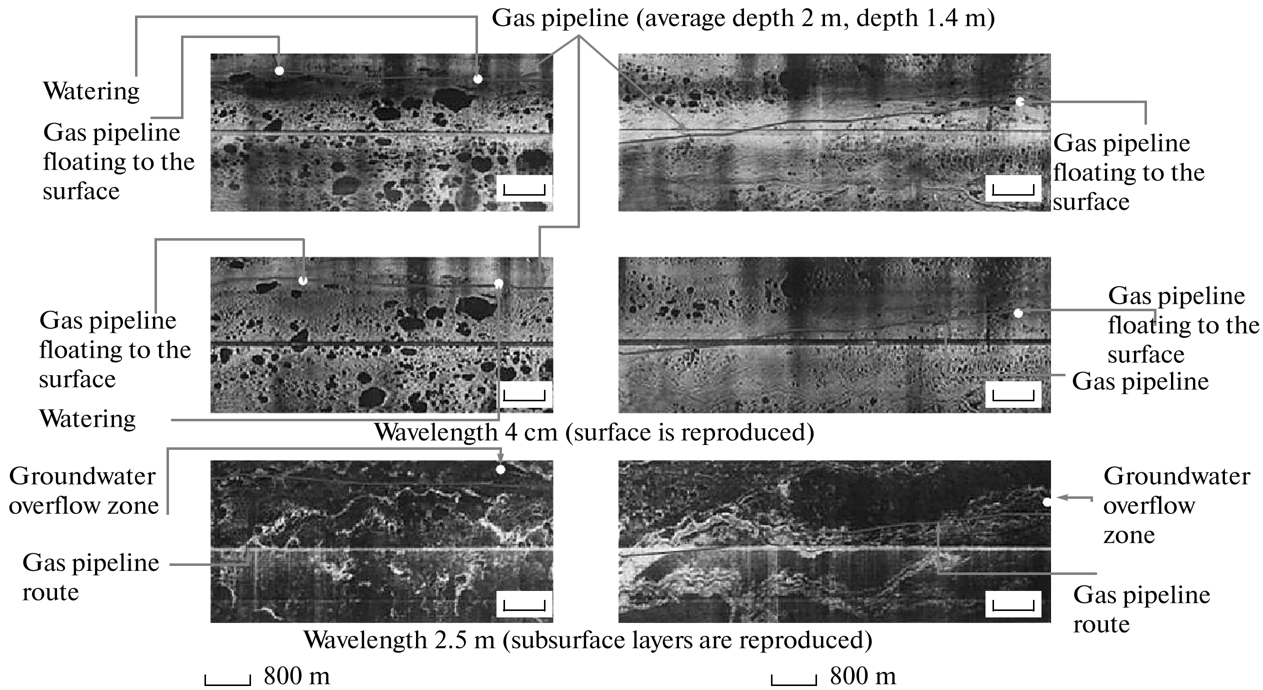

Fig. 8. Multifrequency RIs in segments of the Urengoi–Surgut–Chelyabinsk gas pipeline route.

pipeline. The RI fragments obtained in the meter range ($\lambda_2 = 2.5$ m) show the gas pipeline and the zones of groundwater overflow (Figs. 7, 8, bottom). Floating of the gas pipeline toward the surface and watering zones were revealed on RI fragments obtained in the centimeter range ($\lambda_1 = 4$ cm).

Space Monitoring of Sea Surface Pollution by Oil

The space methods and technologies are very effectively used to monitor areas of seawater pollution by oil related to sea transport, oil platform, and subsea oil pipeline accidents (Bondur, 1987, 1995, 2004; Bondur and Grebenyuk, 2001).

Figures 9 and 10 (color inserts) illustrate space monitoring of the consequences of the accident on the British Petroleum platform in the Gulf of Mexico that occurred in April 2010.

Figure 9 presents the space images obtained from the Aqua satellite on April 25, May 9, and July 12, 2010, and from the Terra satellite on April 25, 2010, where the consequences of this accident in the gulf area are clearly defined.

Figure 10 illustrates processing of the multispectral space image obtained on May 31, 2010, from the Terra satellite (MODIS equipment).

The preliminary data processing including decompression, calibration, and geographic binding of data was performed automatically. The thematic processing was performed in the interactive mode and consisted in the following main procedures: masking the land, detection of cloudiness, identification of the range of interest, selection of optimal classification parameters, classification of the range of interest using the ISODATA algorithm, identification of classes corresponding to two levels of water surface pollution by oil, and vectorization of achieved results and their integration into GIS.

Figure 10 presents the initial space image, the result of classification by the cluster analysis method, and the map with the oil pollution area in the Google Earth system.

Figure 11 (color inserts) illustrates the processing of RI obtained on December 28, 2005, from the Radarsat satellite for the oil production area on the Caspian Sea shelf (Oil Stones). Figure 11a presents the initial space image and its enlarged fragments. Figure 11b (left) shows the images demonstrating the succession of intermediate processing stages, and the results of classification performed using the maximum likelihood method are presented on the right.

The oil pollution areas and artificial sea structures are clearly defined on the right fragment of Fig. 11b.

Monitoring Ice Conditions in Arctic Oil and Gas Areas

Below, we present some examples of space monitoring of ice conditions in Arctic regions of Russia. Figure 12 (color inserts) illustrates an analysis of ice conditions in the Arctic Ocean based on RIs obtained from the Radarsat-1 satellite. The space monitoring of ice conditions included the following main procedures: planning radar surveys in the specified areas,

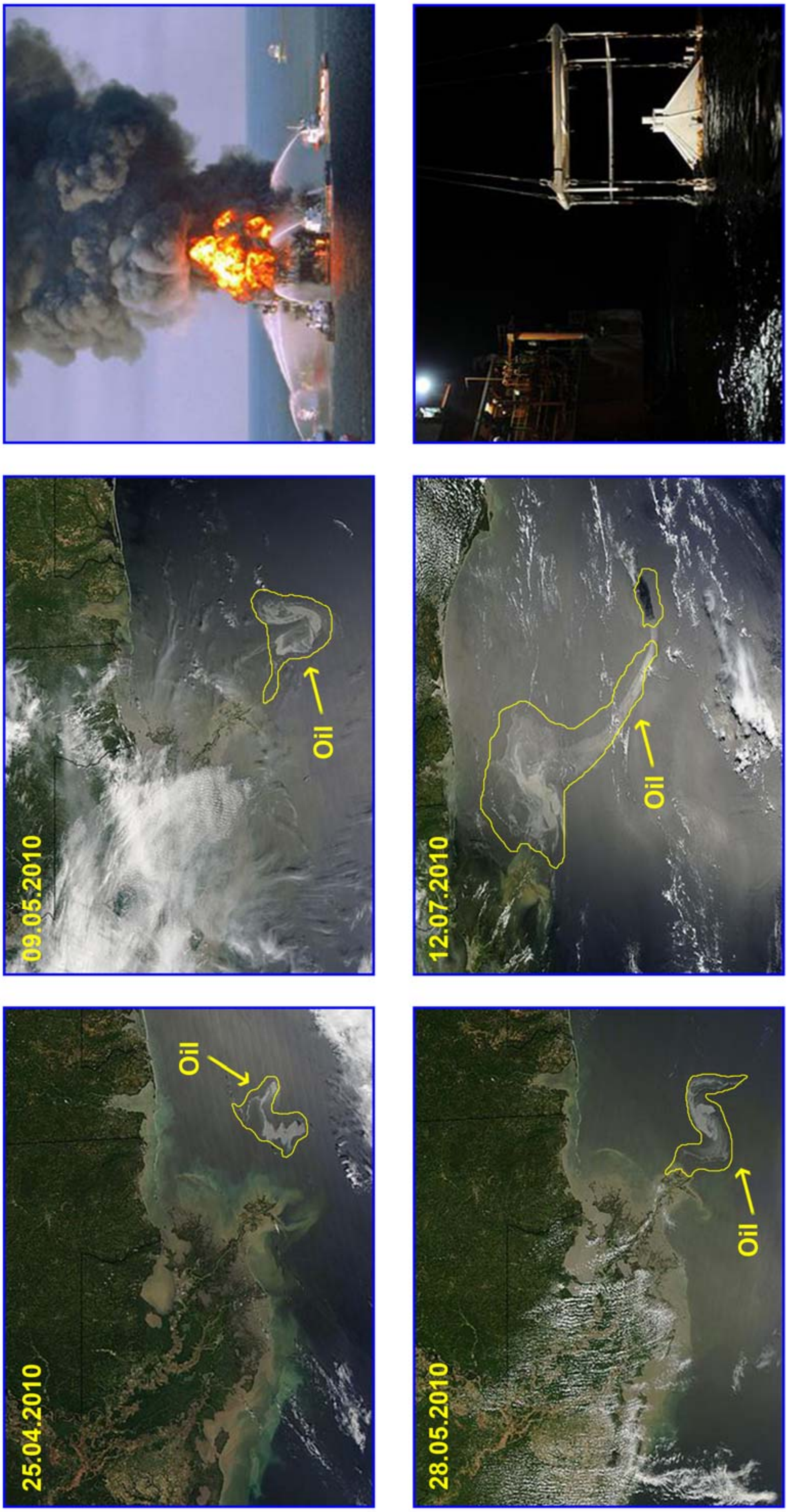

Fig. 9. Space monitoring of consequences of the accident on the oil platform in the Gulf of Mexico (April –July 2010).

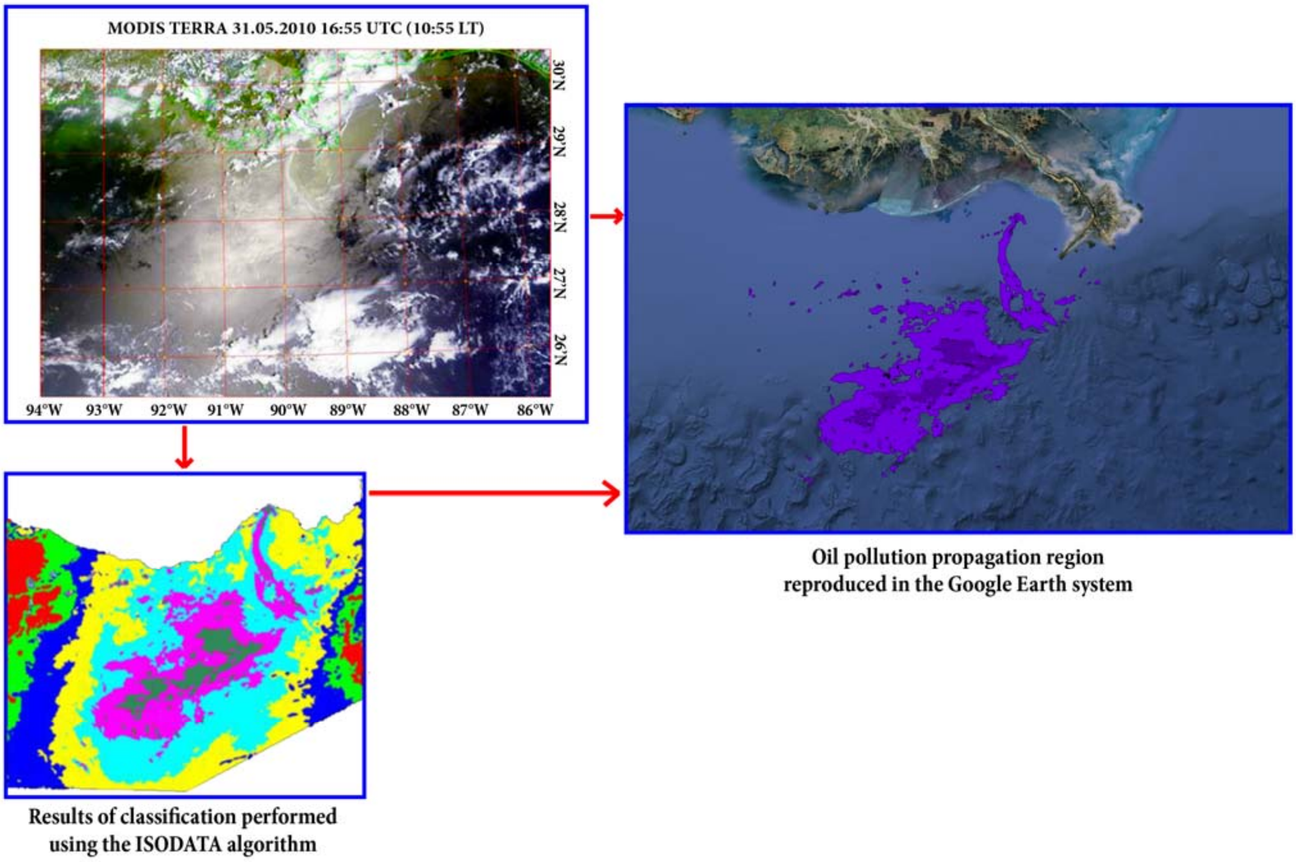

Fig. 10. Mapping oil pollution propagation in the Gulf of Mexico according to the results of processing of the image obtained on May 31, 2010, from the Terra satellite.

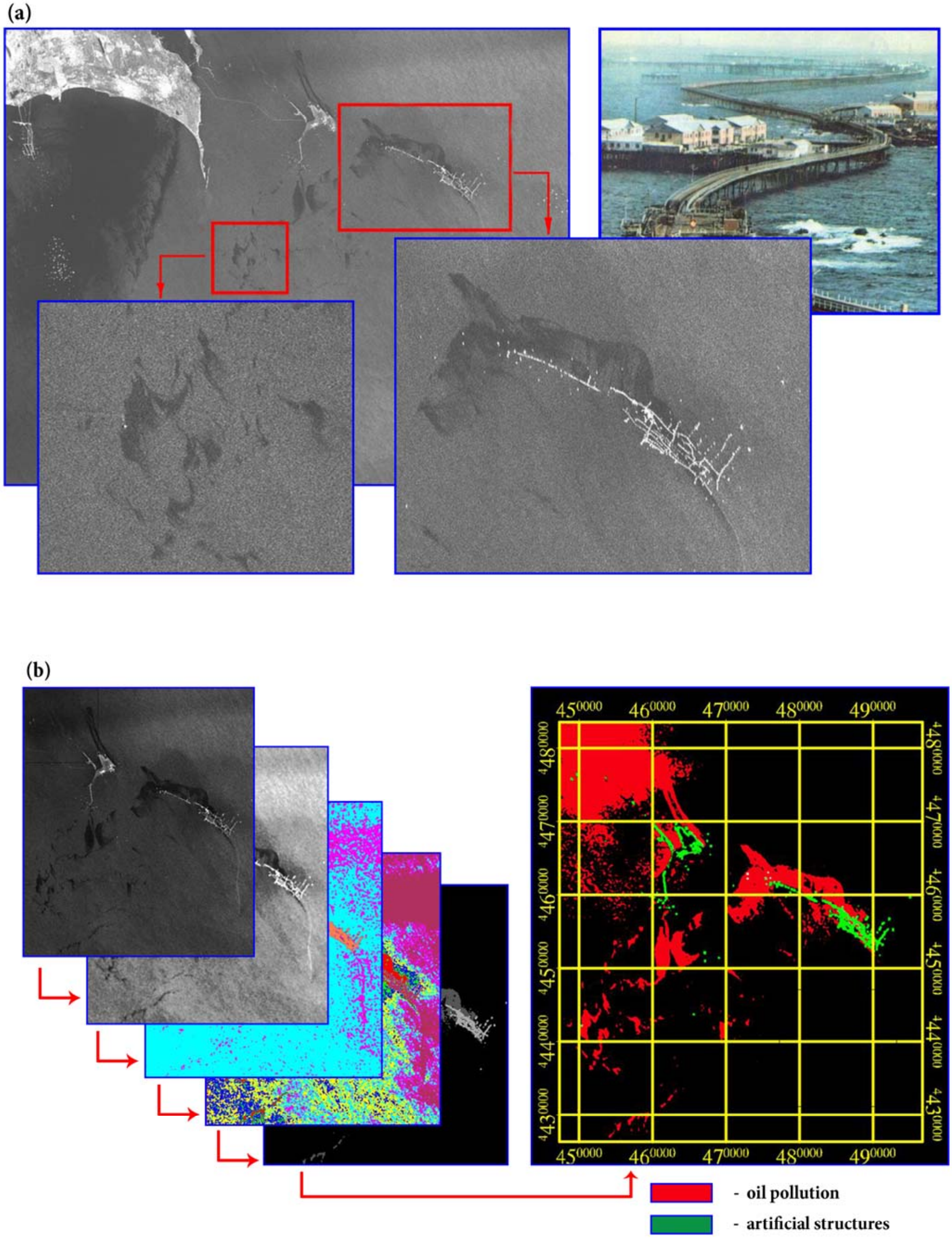

Fig. 11. Space radar monitoring of oil pollution in the Caspian Sea (Oil Stones): (a) image obtained by the Radarsat – 1 satellite (December 28, 2005, 14:30 UTC) and its enlarged fragments ; (b) example of thematic space RI processing in order to reveal oil pollution in the Caspian Sea (Oil Stones).

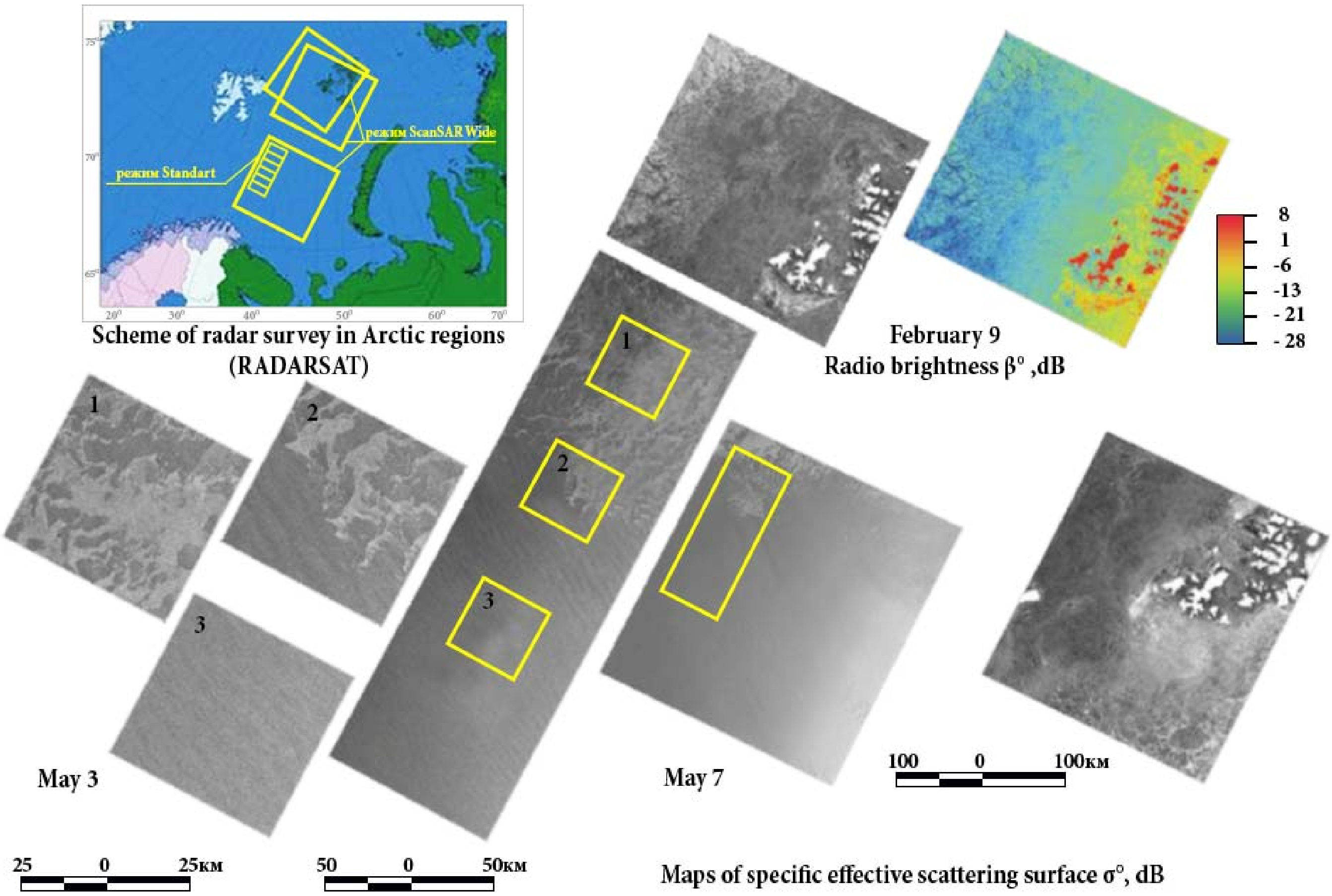

Fig. 12. Monitoring of ice conditions in the Arctic oil and gas region based on RIs.

obtaining and preliminarily processing images, preliminarily analyzing images, constructing time series of geographically superimposed image fragments and identifying the ranges of interest, calculating radio brightness fields β° (dB), and forming information products for different dates.

Information products formed for different dates are used to analyze ice conditions in the studied region.

CONCLUSIONS

We analyzed the current tendencies in the development of RSE and justified the urgency and necessity of aerospace methods and technologies used to monitor oil and gas areas and facilities. We classified the main problems in the oil and gas industry which can be solved using aerospace methods.

We proposed the principles for organizing aerospace monitoring for the purpose of oil and gas industry and described the stages of data acquisition and processing and ways of their transmission from sources (different satellites and aircraft with different RSE equipment) to consumers using the up-to-date geoinformation technologies.

We analyzed the physical mechanisms responsible for the possibilities of aerospace monitoring oil and gas areas in order to assess their potential for the presence of hydrocarbons and assess the state and control of the effect of oil and gas facilities on the environment.

We indicated that the possibilities of such monitoring are related to registering changes in the characteristics of electromagnetic radiation and gamma rays and anomalies of the gravitational and magnetic fields, and to recording the structural–morphological topographic features registered using different aerospace instruments. The main information parameters registered by aerospace methods during the environmental monitoring of oil and gas facilities on land and on the sea are thermal contrasts in the areas where pollutants appear owing to a change in the physical temperature and emission coefficients, brightness contrast due to differences in the spectral brightness coefficients of a facility and background, a change in fluorescence spectra and permittivity, deformations of the surface wave spectra due to smoothing of its HF components when oil, oil products, and gas components are discharged into the marine environment, and Doppler frequency shift of radar signals owing to the appearance of currents in the area where oil and gas facilities operate.

The structural–morphological features of the lineament network and oval–ring formations, specific isometric topographic features represented by weak neotectonic uplifts most favorable for the location of oil and gas traps, and variations in the fields of spectral brightness, temperature, gamma rays, and magnetic and gravitational field anomalies in the areas of positive morphometric topographic anomalies related to the oil and gas content are informative indications used to search and explore for oil and gas deposits and evaluate the hydrocarbon potential using remote methods.

These indications can be registered by multispectral and hyperspectral RS equipment, IR and microwave radiometers, radio interferometers, altimeters, satellite navigation systems, and instruments used to register the magnetic and gravitational fields and by passive gamma spectrometers.

We indicated that the prospects to increase the effectiveness of solving the oil and gas monitoring problems are related to the utilization of new methods, technologies, and RS equipment, development and application of new methods for processing aerospace data, application of present-day geoinformation technologies, and complexing of aerospace and ground data.

We demonstrated how the aerospace methods and technologies can be used to monitor the ecological conditions in oil and gas production areas; monitor pipelines using a two-frequency radar; reveal sea surface pollution by oil, including in the accident on the oil platform in the Gulf of Mexico; and control ice conditions in the Arctic oil and gas region.

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