INTRODUCTION†

The Board of JSC “Gazprom” adopted in 2000 the Program of Aerospace Monitoring. An ultimate goal of the Program is to make an overall system for the resource monitoring of areas and more than 200 thousand kilometers length of pipelines and also to make a pipeline-inner diagnostics, ground-level inspection, aero-monitoring and monitoring with a space segment at the final stage of the development. The space segment is supposed to be supplied with either conventional system for the multispectral space sensing in optical range or more sensitive research equipment for hyperspectral monitoring of production areas, pipelines and of the Earth’s limb. The latter approach purposes to predict the tectonic processes in the Earth’s crust that is necessary for estimation of the pipelines geotechnical state.

In 2000 the Russian Aerospace Agency opened a tender for the development of a SC for the hyperspectral sensing of production areas (the Winner of this tender is CSDB “Progress” located in Samara) and another tender for the development of optical hyperspectral SC for the Earth’s limb exploration (the Winner of this tender is NIIEM located in Istra City near Moscow). Besides, JSC “Gazprom” develops together with aerospace industry the project for hyperspectral monitoring of pipelines which combines the hyperspectral resolution of 1 *nm* in 700 spectral lines and of 3-5 *m* spatial resolution, and precise system of pre-programed scanning of pipelines with narrow angle of view. The hyperspectral instruments for airborne and space locations are designed by “Reagent” Research & Development Center (R&DC) in Moscow.

As a first step on the way to develop the space segment a specialized airborne laboratory has been built using technology developed by “Reagent”

---

† This paper was presented at the 3rd International IAA Symposium “Small Satellites for Earth Observation”, 2 – 6, April, 2001, Berlin, Germany and now is represented here with light changes.

R&DC by the order of JSC “Gazprom”. This hyperspectrometer sample provides the spectral resolution within 1.0 - 2.0 nm. The main purpose of the development of the airborne sample is to estimate the hyperspectral information efficiency using the objects of JSC “Gazprom”. Achievements in the sensing technology and testing instruments developed are confirmed by certified test flights over the gas pipelines near Gryazevets-Myishkin area situated at the European part of Russia. The tests were successfully carried out in August, 2000 and 2001. The industrial monitoring of the northern pipelines with employing of the hyperspectral instruments was successfully carried out in September, 2000 and 2001 by the Corporation “EcoTech-North” by the order of “Yamburggasdobyicha” and of the Department of Science, New Technology and Ecology of “Gazprom”.

The flying lab has been also supplied apart from the hyperspectral instruments with conventional instruments for multispectral air photography, infrared scanner, time-reference system and with the coordinate binding based on GPS/GLONAS navigation systems. Simultaneously with on-ground exploration of the pipelines by conventional means, the new approach which uses a geo-radar for the exploration of the Earth below the ground level was tested.

1. PROBLEMS OF PIPELINE MONITORING

Production, transportation, and processing of gas render noticeable affect the environment. Qualitative and quantitative estimations of characteristics of the effect of the environment on objects of the gas industry and, also, the effect of objects of this industry on the environment cause the modern progress of the gas complex. In this way, to solve the following tasks is supposed to be important:

- The environment of the gas complex objects can result in emergencies and, therefore, it requires to execute a scheduled work to recover the complex segments being in before-emergence condition. This poses a task to monitor the gas complex objects with the purpose to inspect and forecast the approaching to the emergency condition.

- Nowadays the cost of gas and other mineral products is augmented by the value of penalties and allocations to recover the ecology of the gas production areas. To avoid cutting the profitability of the gas complex, the monitoring system has to estimate the real ecological hazard to minimize the penalties for the environment recovery. Also, this system should separate the hazard purely made by the gas complex from that of the other industrial objects and pollutions of the natural origin. It is necessary to analyze the tendency in the gas complex which affects the environment with the purpose to prevent violations of the ecology at earliest stage with minimum efforts.
- Development of the gas complex also requires a permanent completion of the operational deposits and to search for the new ones.
- To lay pipelines it is necessary to be familiar with the geological structure of prospective directions of the pipelines and to evaluate the geoindustrial effects of pipeline beforehand. It is possible to evaluate such effects analyzing the progress of the complex already operates.

The tasks listed above correlate with the tasks arising in other areas of industry. The methods and technological means developed for that can be successfully used in the close areas of human activity. It may increase the total value of monitoring.

2. COMPLEX MONITORING OF PIPELINES AND NOTHERN RESOURCE FIELDS

An example of the combined approach to arrange the complex monitoring is on-ground and airborne explorations which were carried out in August and September, 2000 in framework of the Program of the aerospace and on-ground explorations of the Yamburg Oil-Gas-Condensate Fields (YOGCF). The interest to the northern territories is stimulated by close relationship between northern gas papelines and the permafrost soils. This determines the geotechnical pipeline systems class. The reliability of pipelines is governed by the mechanism of interaction in these geotechnical systems.

The set of diagnostic methods is defined by the features in this problem and, therefore, includes:

- aerospace monitoring of the pipelines and territory of fields;
- landscape, engineering-geologic exploration;
- measuring of parameters of tight-strained state and outside defectoscopy of pipelines;
- development of mathematical forecasting models for linking the dynamics of changes in natural, first of all, permafrost conditions with reliability and the residual lifetime of pipelines;
- development of intelligent systems combining geographical information systems, technological databases for the analysis, and recommendation blocks.

The complex examinations conducted on YOGCF territory, are labour-consuming and extra expensive. However, they are the basis for the development of low-cost and operative approaches engaging the methods for space monitoring of the Earth.

Since there is a sufficient experience in combined ground-level and airborne examinations of the local regions, in future it is possible to ensure operative and low-cost monitoring of all pipeline network. Also, it is possible to perform reconnaissance and contouring of the resource fields through a space monitoring of Earth only. In this way the airborne monitoring is implemented first as a low-cost one and fast to be implemented, and as an indispensable device in the subsequent embodying of space monitoring program.

The practice of examination of YOGCF demonstrates that the monitoring based on the conventional approaches of monitoring has a limited applicability. The images of the high spatial resolution, with reference to the linear objects masked by two-meter stratum of a soil do not give us an essential increase of self-descriptiveness.

Hyperspectral survey containing up to thousand of spectral channels provides a qualitative raise of the information capacity of extremely low-cost, in terms of the hardware solution, monitoring in visible and SWIR bands. The airborne monitoring is a part of a comprehensive diagnostic Program of northern pipelines of the YOGCF geotechnical system. Diagnostic program includes the following items:

- permafrost, landscape, engineering-geologic examinations;
- measuring of parameters of tight-strained state and outer defectoscopy of pipe lines;
- making of mathematical prediction models which combine dynamics of variation in natural, first of all, permafrost conditions with the reliability and life resource of pipelines;
- making intelligent systems integrant geographical information systems, technological databases for the analysis, and recommendation blocks of repair, modes and gas transportation technologies.

For the examination of gas pipelines and depositing territories in Yamburg region the following equipment was used:

- airborne camera (ABC) such as TK-10 with 100-mm focus, capture 1,8 H of flight and command units for the sight ABC operation control the electronic;
- solar reflective hyperspectral device (engineered by "Reagent" R&DC.)

Hyperspectral instrumentation was designed to monitor spectral characteristics of the communications and trunks in absorption line strips, direct and diffuse reflection in near ultraviolet, visual and near infrared spectrum range, in two polarizations. The spectral decomposition is carried out through diffraction gratings. The spectral resolution is 1.0-2.0 nm. Field of view of the device is equal to 12 degrees. The spatial resolution at 1000 m height is about one meter in a perpendicular to current plane traffic direction and about two meter in parallel at the plane cruising speed. Hyperspectral instrumentation embedies a modular approach. Each module is designed for operation in a particular spectral range and, in average, is provided with 200 spectral channels.

In year 2000 and 2001 expedition pioneering four such modules enveloping a visible band of 0.4-0.85 μm were tested. Other four modules covering the band of 0.3-1.8 μm were scheduled in year 2004 expeditions and the gamut from 0.3 up to 1.6 μm is overlapped. The information received by modules is converted to the video signal and transmitted to the recording unit. The received data is fixed to the terrain by the synchronous video data which are received from service video camera involved in the complex, ABC photo data, SC navigator, and onboard inertial navigation system.

First, the complex was proved over tundra, in the land with permafrost, with no woods and big bushes. Hyperspectral data are clocked by a common signals and are convenient for the subsequent co-processing.

- Scanning radiometer "AGROS". The device supplies spectral zoned images in visual, near and far (8-12 μm) infrared (IR) spectrum bands. The information of a radiometer ensures recovering "natural" underlying surface temperature in a range from -40 up to +50 degrees C to within 0.3 degrees. Resolving ability at the altitude of one kilometer is not worse than one meter. The strip of capture constitutes 1.4 altitude of flight.

- ABC navigation complex (ABCN). Within a combination of a complex with GPS and onboard PC-type computer, ABCN allows us to obtain navigational data and to realize the steering calculations of manual air navigation displaying them at the screen as it is required (intermediate waypoints, planar coordinates, data on the rate, velocity and deviation from required course). The conjugation with ABC allows us to file and to issue by other ABC systems the moment of actuation ABC locks and also to store them in a computer memory with binding to coordinates. For the express analysis the data of video sensing, ABC and AGROS, simple correlation handling for separate hyperspectral sub-bands are used. The instrumental data of ground-level surveys of the year 2000 is subject for the lab processing at a present time.

The presented sampling of the hyperspectral monitoring data solves a main problem of pre-processing (i.e. normalization, correlation analysis and centering). The diagnostic of reference anomalies on trunks are detected. The continuous processing of the data set is made at present time by standard technique.

The airborne laboratory surveys gas lines made for a series of objects passing YOGCF territory, trunks of Yamburg - Nida, motorway Yamburg – New Urengoi, collector and the other infrastructure. The duration of sensing is more than 30 hours in flight.

3. HYPERSPECTRAL MONITORING DATA PROCESSING

The hyperspectral monitoring data are recorded on the magnetic tape accompanied by time markers. They permit to realize their joint binding for further laboratory processing. The received records are digitized and computer processed. The processing consists of several stages. At the first stage the hardware effects (i.e. distortion and inhomogeneity of the sensitivity) are eliminated. The second stage implies the uniform coordinate binding of the data. At the third stage the hyperspectral data of correlation processing is performed using allocation maps of correlation functions which concern the given test field.

For obviousness the joint maps of correlation with several test fields are made. Thus, the correlation of one test field is valued till the given functional to a level and at excess of this level is designed by a pseudocolour which is particular for each test field.

The treatment includes coprocessing hyperspectral data with other aircraft complex channels, data of ground-level measurings on the pipe line – permafroze geotechnical system patterns basis. The illustrative materials demonstrating primary hyperspectral information in one of modules in a subband 0.45-0.65 μm are presented in Figures 1-5 in the following consequence [6,7].

Figs.1.1-1.2 show halftone image received by convolution hyperspectral information in a spectral band 0.45-0.65 μm.

Figs.2.1-2.2 show correlation convolution (colour image), made on 9 test fields including reference points such that water, messes, sand, point on the naked pipe line etc. At build-up of figures the hyperspectral data in each point were set norms per unit, i.e. the dependence of an integrated reflectivity on a place and requirements of shooting was eliminated.

Figs. 3.1-3.4 show the same as Fig.2 but each in one of colors.

Fig.4 demonstrates the image of the sub-aircraft point which is noted by cross-hairs in the first two figures. The line on the CCD image exhibits field (area) of synchronous hyperspectral shooting.

Fig.5 shows gray scale image hyperspectral shooting gauged and normalized on a curve of a gear transmission of the atmosphere. The vertical axis is spatial coordinate. The horizontal axis is spectral coordinate in a gamut 0.45-0.65 microns.

4. BASIC TECHNIQUES FOR BUILDING UP OF THE HYPERSPECTRAL MICRO SATELLITE

The Earth optical monitoring future is bound to the development of the hyperspectral observation techniques. The typical spectral resolution of $\Delta\lambda \sim 10$ nm of the operating multispectral optical systems employed now will be replaced with spectral resolution of $\Delta\lambda \sim 1$nm and further down to $\Delta\lambda \sim 0.1$nm. Reaching for a such high spectral resolution gives a steep surge to the equipment sensitivity requirements or the equivalent expanding of the optical systems aperture.

Whereas construction of the large aperture optical instruments with complex systems of image stabilization at the photo-receiver’s focal plane highly boosts the cost of such systems, increases the development and start times. Therefore, the major trend in the Earth monitoring equipment designing in terms of commercial use is finding the way to reduce the size, mass and power consumption parameters as well as to considerably lessen the requirements for the SC platform stabilization. The on-line flexibility and globalness of the observations are not the obligatory factors in the commercial use. This allows us to operate the optical electronic system according to the user request (e.g. via Internet) pointing out the local observation area and the specific spectral lines (or their suspension) at which the observation should be made. Therewith one may evade the high redundancy degree of the conventional observations.

The practical realization of this ideology can be based on the two technological achievements. They are programmable acousto-optical filter and separate photons counting device with the high space-time resolution [1]. Principles of the hyperspectral observation technique are illustrated on Fig.6.

4.1. Acousto-Optical Tunable Filters for Visible and UV Lights

Acousto-optical tunable filters (AOTF) with optical size of approximately 8-10 mm for visible and ultraviolet spectrum on the base of TeO_2 and KH_2PO_4 (denoted by KDP) crystals are developed and manufactured by “Reagent” R&DC. These devices have the highest space, frequency and time simultaneous resolutions. The spectral resolution is better than one *nm*. The frequency band width of both filters is 55-90 MHz that allows us to use only one light frequency generator with a row of different power amplifiers. Acoustic power level for the AOTF based on TeO_2 and KDP is about 1 W and 5 W respectively. The optical tuning is carried out by means of software. The first AOTF has been similarly constructed to the one reported by I.C.Chang. 163° YZ-cut $LiNbO_3$ transducer was bonded to the TeO_2 crystal with In metal.

The most significant advantage of this type of AOTF is its low input electric power required. The optical tuning is carried out by means of software and the filter randomly permits any wavelength within its spectral range in less then 15 msec. The KDP crystal has been used in the designing and fabrication of AO cells for UV spectrum [2,3]. Specifications of the noncollinear AOTF on the KDP crystal available are as follows:

Spectral range, nm	250...400
Optical aperture size, mm	3...8
Angular aperture size, degree	0.5...6
Input optical polarization	Linear
Access time, ms	2...5
RF frequency range, MHz	55…130

Specifications of the noncollinear AOTF on the TeO_2 available are as follows:

Spectral resolution, nm	1...10
Spectral range, nm	400…2000
Spectral resolution, nm	1..10
Optical aperture size, mm	3...8
Input optical polarization	Linear
Access time, sec	5..13
RF frequency range, MHz	50…130

The spatial resolution of AOTF is limited by diffraction and depends on the optical aperture size.

4.2. The Micro-Channel Plate (MCP) Photon Detectors

The most sensitive detectors known at the moment are those based on the MCP technology which provide (unlike the CCD-storing systems) detection of the photon beam in the single photon sequential analysis mode determining the coordinates at the 2D focal plane with high spatial resolution along with a high time resolution accessible to super-speed CCD-systems. The technology of these detectors is based on the principle of conversion of a weak photon beam into the photo-electron current from the photo-cathode surface and its subsequent amplification by ~10^6 factor with the MCP while preserving the spatial-time resolution (with the accuracy of ~20 μm in space and 10^{-9} s in time). Further on one of the multi anode collector system read-out options of the remitted electron flow yields the X, Y, t coordinates by the computation unit. The best aerospace specimen of such systems (MAMA-detector) reaches the 1000 x 1000 pixel of spatial resolution and the photo-electron counting rate of 10^6 s^{-1} under the photo-cathode quantum output of ~10-20%.

One of this detector version was developed by “Reagent” R&DC [4,5]. It differs from the MAMA-detector by simplified collector system and more thorough signal processing mathematics. While properties of the “Reagent” R&DC variant are preserved close to that of the MAMA, the former can be implemented within one kg mass – one liter volume and ten watt power consumption. We should note that the detector’s engine noise is determined by the photo-cathode noise and no cooling is required. In the framework of this project the rate of photon counting will be increased in 100-1000 times.

4.3. Star-Tracker

The MCP detector is a proper star-tracker due to high sensitivity and high space-time resolution. Essential factor is that mathematical conversion of the MCP-detector data may compensate the star-tracker’s angular motion with sufficient high rate by transferring to the proper reference system [4]. Highly accurate determination of angular motion of the optical axis is the result of this procedure. The high sensitivity of the MCP-detectors allows us to construct a narrow-angle star-tracker which recognizes the starry sky image and does not require the basis-system of bright stars.

5. GENERAL CONCEPT OF SCIENTIFIC INSTRUMENTS ENERGY ESTIMATES

Cutting down the scope angle θ_0 to 10^{-3} rad under the extended effective aperture diameter of the input lens eyes up to 15 cm makes it possible, as on Fig.6, to sharpen the angular resolution to $\Delta\theta\sim10^{-5}$ rad that corresponds at H~500 km to 3-5 m of the spatial resolution, sufficient to solve the ecological monitoring tasks in terms of the local Earth parts. In this case $W_0\sim10^{-2}$ W/km·cm^2·str in the visual band, the input telescope effective area S~225 cm^2 , the scope solid angle $\theta_0\sim10^{-6}$ rad^2, $P_{qw}\sim10^{-1}$, χ_{AOTF} ~1/3, and assume $\Delta\lambda\sim1$ nm for effective hyperspectral analysis than the MCP photon counting rate amounts to:

$$N_{ph/s} \sim W_F \cdot \Delta\lambda \cdot \chi_{AOTF} \cdot P_{qw} \cdot S \cdot \theta_{ap}^2 \cdot 2 \cdot 10^{18} \approx 10^8\, ph/s\,,$$

i.e. the photon number is rather small and the photon counting mode realization is required. An image of 100 brighten grades is available in the 10 narrow spectral band (or 10 correlation functions which are equivalent to the final result of the hyperspectral cube processing) from the 1500 × 1500 m area during time interval τ = 100 s.

A detector combined with the star-tracker provides photon coordinates fixing an accuracy of 5 m with respect to the ground based reference coordinate. Whereas the detector plane image hold system can be a rough mechanical circuit with an accuracy of ~10^{-3} rad that implies no problem. While the given local plot can be traced by the SC during ~100 s of flight within the strip width of ~1000 km. This time allows us to gain the hyperspectral stereo image due to synthesizing of the base during the flight. The complete system on the base of the today technologies can be designed within ~4 liter of volume and ~4 kg of mass with the power consumption of ~15 W. For small satellite with weight m = 200 kg the number of simultaneously measured spectral bands can be increased up to 1000 and observed area can be increased considerably. The number of the image brightness can be increased up to 500 by means of adaptive approach to using hyperspectrometer resources.

AKNOWLEDGEMENTS

We would like to thank: Makredenko, A.Victorov, A.Dudkin (Rosaviacosmos, Depatment of Remote Sensing) for analysis and expertise of the project; C.Kulik, D.Gorovec (Rosaviacosmos) for collaboration with European Union; A.Ananenkov, E.Dedikov (Gazprom, Depatment of Science and Technology), Yamburggazdobicha Company for the flight experiments assistance. Also this work is partly supported by ISTC (project: 23-23) and RBSF (project: 03-01-00-652).

REFERENCES

1. *Rodionov I., Ovchinnikov M.,* Microsatellite for Remote Sounding of Environment, Digest of the IAA International Symposium "Small Satellites for Earth Observation", 4-8 November, 1996, Berlin, Germany, pp.225-229.
2. *Rodionov I., Ponomarev A. at.all,* Active Optical Ecological Monitoring // SPIE Vol. 2107, p.476-494.
3. *Rodionov I., Ponomarev A. at.all,* Wide Aperture Acousto-Optic Turnable Filters for Visible and UV Lights // SPIE Vol.2449, p.200-207.
4. *Rodionov I., Rodionova I., Ovchinnikov M.,* The Microsatellite for Remote Exploration of Environment // SPIE,1997, Vol.3119, №3119-11.
5. *Rodionov I., Rodionova I., Ovchinnikov M.,* Approaches to Develop the Earth Observing Systems Based on the Turnable Acousto-Optical Filter and Separate Photons Counter with MCP // SPIE, 1997, Vol.3117, №3117-10.
6. *Vorontsov D.V., Orlov A.G. Kalinin A.P., Rodionov A.I., Shilov I.B., Rodionov I.D., Lyubimov V.N., Osipov A.F.* Usage of the Hyperspectral Measurements for Remote Sensing of the Earth. Preprint of the Institute for Problems in Mechanics of RAS, 2002, №702 (in Russian)
7. *Vorontsov D.V., Orlov A.G. Kalinin A.P., Rodionov A.I., Shilov I.B., Rodionov I.D., Lyubimov V.N., Osipov A.F.* Sub-pixel Processing of the Hyperspectral Measurements. Preprint of the Institute for Problems in Mechanics of RAS, 2002, №703 (in Russian)
8. *Khrenov N.N., Dmitrievsky A.N., Ananenkov A.G., Sheremet V.V., Ponomarev A.A., Rodionov I.D.* Hyperspectral Aerospace Monitoring of Pipe-lines and Deposit Areas // Science and Engineering in Gas-Industry, Moscow, 2001, №2-3, pp.37-46 (in Russian)