Multiscale Space Monitoring in the Environmental Protection Tasks of Mining Territories of the Barents Euro-Arctic Region of Russia

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Abstract: The paper considers the current state of the tasks and prospects of automated remote monitoring of mining objects and territories of mining enterprises to solve the environmental protection problems. Technical features of space technologies of optical-electronic and radar sounding of the Earth's surface are described. The methodological approach has been justified and implemented to the multiscale assessment and risk management for the environment through a comprehensive integrated analysis of multi-level spatial data based on the use of applied geographic information systems and web-resources. The separate results of the studies are shown in the solution of the tasks of the areal prognostic monitoring to ensure industrial and environmental safety of mining enterprises by the example of the Russian Barents Euro-Arctic region. Spatial zoning of the territory and categorization of environmental risks by scale and degree of danger has been performed by using satellite high-precision optical-electronic and radar space imaging. The authors have formulated proposals on practical application of multiscale space monitoring of mining territories, including creation of digital 3D models of relief, assessment of displacements and deformations of surface mining structures, zoning of the territory and risks ranking by degree of hazard, as well as geoinformation support for solving tasks of industrial and environmental safety and environmental protection.

1 INTRODUCTION

The Federal Law of the Russian Federation "On environmental protection"defines the legal basis of state policyand provides a balanced solution to socio-economic problems and creation of favorable conditions for biological diversity of natural resources to meet the needs of present and future generations, strengthen law enforcement and achieve environmental security. In accordance with the Law, environmental protection issues are given much attention (Ashikhmina and Kaverina, 2022; Kolesnikov, 2022; Repin et al, 2022).

The mining industry is associated with various environmental risks: geological, hydrogeological, engineering, construction, meteorological, etc. The economic damage due to accidents caused by unaccounted and uncontrolled risks reaches significant costs, up to shutting down and even mothballing the mining enterprise.

The purpose of mining objects and territories monitoring is to assess and predict dangerous events in order to prevent and minimize technogenic disasters (Melnikov et al, 2018; Kalashnik et al, 2022). Modern observation systems apply remote and automated technologies based on BIG DATA, CLOUDE and AI (McGaughey, 2020). Each system has distinctive features and area of application. High detail and accuracy of measurements are achieved by stationary and in-situ measuring means, and information vaue and scales of coverage are provided by space and unmanned aerial vehicles (Kalashnik et al, 2022; Maus et al, 2020; Ponomarenko et al, 2020).

The most promising tool in geoinformation support of mining operations is space monitoring (Kalashnik et al, 2022; Girija et al, 2019; Maus et al, 2020; McGaughey, 2020; Melnikov et al, 2015; Ponomarenko et al, 2020; Werner et al, 2019; Yang et al, 2020). There are varieties of spacecraft constellations designed to obtain information on

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physical, chemical and biological aspects of the environment (Global Satellite-Based, 2021). The space industry is dynamically evolving towards the creation of an intelligent geometaverse (AI-GEO-META), focused on the virtual interaction between people and technology when dealing with a set of spatial data in real time (Melikhov, 2022).

Actual issues and directions of studies on this topic relate to the development of fundamental knowledge and the search for practical solutions related to the organization of a multifunctional system-structured observation program (retrospective, operational, analytical, thematic, predictive, etc.) in one or a group of mining enterprises, which provides the stability of the collection and transfer of geospatial information in a single digital space (Cheskidov et al, 2019; Kornilkov et al, 2020; Lacroix et al, 2019; Melikhov, 2022; Ponomarenko et al, 2022).

2 METHODS

Multiscale space monitoring of environmental risks in the Barents Euro-Arctic region is carried out by multilevel and interdisciplinary studies based on a comprehensive integrated analysis of multilayer spatial data (satellite, geodesic, geophysical, geological, hydrogeological, etc.). The conceptual model of the observation system is structured by the levels of knowledge about the state of the environment and their representation (Figure 1). Setting and specification of tasks on the basis of analysis of empirical experience in similar mining-geological, climatic and other conditions is carried out to optimize the choice of technical support. Space (optical-electronic and radar systems) and digital (GIS and web-resources) technologies provide collection, processing and distribution of thematic information through stationary systems or mobile technical devices. Specialists can remotely observe technogenic (an industrial site, capital and linear structures, mining machinery and equipment), natural (protected areas, forest and water resources, soil cover, glaciers, atmosphere, biosphere) and natural-technogenic (a combination of both types) environmental objects. The hierarchy of the observation system allows structuring the work with updated spatial data at the local (zone, object), district (group of objects), regional (group of mining enterprises) and national (group of mining enterprises and regions) levels. Scaling determines the degree of detail of measurements and representation of spatial information (in plan and section): from millimeters to hundreds of kilometers. System-structured multiscale environmental risk management using space and digital technologies includes observations and data collection, geospatial analysis and reproduction of finished information products, risk assessment and prediction, and creation of databases and maps of potential risks.

Search and identification of natural and technogenic risks when using spacecraft are performed in the optoelectronic (ultraviolet, visible and infrared) and radar range of the electromagnetic spectrum (Table).

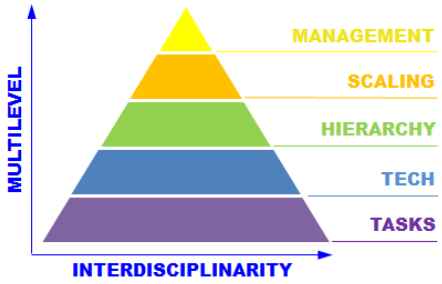


Figure 1: The concept of multiscale assessment and environmental risk management of mining territories in the Barents Euro-Arctic region on the basis of space and digital technologies.

Table: Technical features of spacecraft in the mining territories monitoring.

Survey	A	B	C
Ultraviolet	> 3500	< 2 600	< 1
Visible	> 0.15	40 ÷ 300	1 ÷ 11
Infrared	3.7 ÷ 60	< 290	5 ÷ 10
Radar	1 ÷ 15	< 400	3 ÷ 12

Note: A - spatial resolution, m; B - swath, km;
C - survey periodicity, day.

Optical-electronic systems have high data information value, and radar systems provide all-season observations (Nafieva and Grechishchev, 2020).

Geoinformation resources provide open remote Internet access to spatial data from various satellite missions containing a standardized set of metadata (geographic coordinates, tilt angle, survey time, etc.).

Imagery materials are systematized by data processing levels and are stored on cloud servers. During space imagery decoding, preliminary (radiometric, geometric and atmospheric correction, ortho-transformation) and thematic (spectral transformation and spatial filtering) processing of spatial data based on visual and automated methods is performed. The method of interferometry of constant reflectors was used for processing the data

of multi-pass satellite radar survey (Filatov et al, 2017; Melikhov, 2021b). The method includes approaches to the selection of surface objects stably reflecting the radar signal during the observation interval, as well as algorithms for calculating heights and relative displacements. The results of interferometric processing of satellite radar images from ascending and descending satellite passes, using information about the survey geometry and the topography of the controlled territory, were interpreted to estimate the horizontal components of displacements.

The database of multidimensional space imagery data was created using the open cataloguing system Geo Network. To store pre-processed fragments of space imagery, the open DBMS Postgre SQL was used, which supports geo-relation relationship formats, with an additional modification of the standard Image Mosaic JDBC format to store dynamic collections of image fragments. Methods of analytical geometry, geostatistics and cluster analysis were used to assess the spatial irregularity of displacements of mining objects and the day surface of the monitored area.

To assess hydrogeological risks, the following methods were used: system analysis, qualitative and quantitative risk assessments of dangerous filtration-deformation processes, reliability theory of technical systems, analysis and assessment of technogenic risk.

3 RESULTS

The main results of this study were obtained as applied to the territory of one of the mining enterprises in the Barents Euro-Arctic region of Russia. The tasks of identifying and monitoring environmental risks by space monitoring methods were reduced to the localization and tracking of zones of natural and technogenic processes development on the Earth's surface, or on the surface of mining objects, by means of retrospective spatial-analytical and geostatistical analysis. When assessing risks, the initial cartographic information was updated, and multilayer spatial models were designed, which were basis of the forecast modeling of potentially dangerous events. Geoinformation analysis included visualization and automated zoning of the territory, determination of the configuration of objects and their boundaries in time, as well as localization of natural and technogenic displacements and spatial-analytical calculations by interpreting data of dynamic changes on virtual observation testing sites.

The organization of the satellite observation system for displacements of the Earth's surface in mining conditions was based on the radar interferometry (SAR) method using satellite images Sentinel-1 IWSLC level 1 in the mode of interferometric wide band (< 250 km) with spatial resolution 5x20 m.

The SAR method is based on the effect of electromagnetic wave interference and mathematical processing of sequential coherent amplitude-phase measurements with a shift in space. Synthetic aperture radar makes it possible to track displacements with an accuracy of fractions of millimeters to centimeters, depending on the characteristics of the images and the constancy of the media properties. The space images were preliminarily searched and processed; interferograms were built, and phases were scanned and converted into displacements (vertical/horizontal or line-of-sight), taking into account the terrain relief. In particular, Figure 2 shows the radar space images of the mining enterprise territory for two directions of Sentinel-1A satellite motion. Surfaces on which the radar signal arrives at a sharper angle look brighter, as more energy is reflected from them in the opposite direction and vice versa.

As a result, a differential interferogram was calculated, on which points corresponding to stable reflecting objects were selected, and for them the displacement rates in the direction of the radar line of sight were estimated (Figure 3) (Filatov et al, 2017). Negative values of velocities of displacements of selected reflector points correspond to the direction of satellite flight (away from the radar), positive - in the opposite direction. In Figure 4, the negative values of displacements are marked on the side of the mining object, along which the radar signal propagates: on the western side for ascending spans (Figure 4a) and on the eastern side for descending spans (Figure 4b). Based on this, it was concluded that all the boundaries of the object have directions of displacements to its central part.

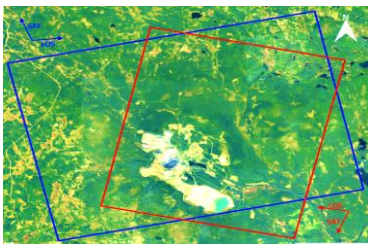
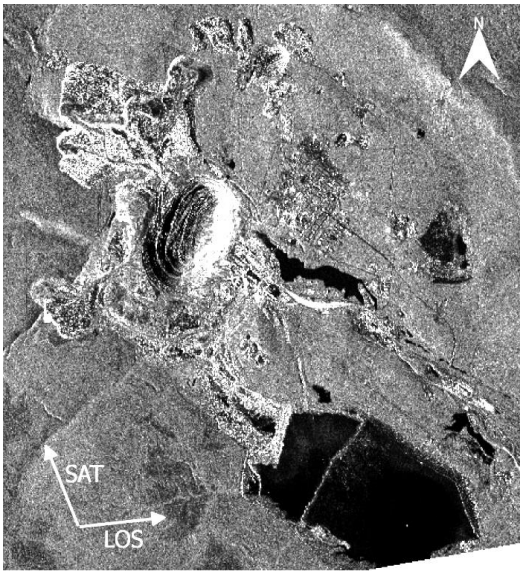


Figure 2: Coverage of the controlled territory of a mining enterprise with Sentinel-1A radar images received from ascending (blue) and descending (red) spans (Filatov et al, 2017).

a)



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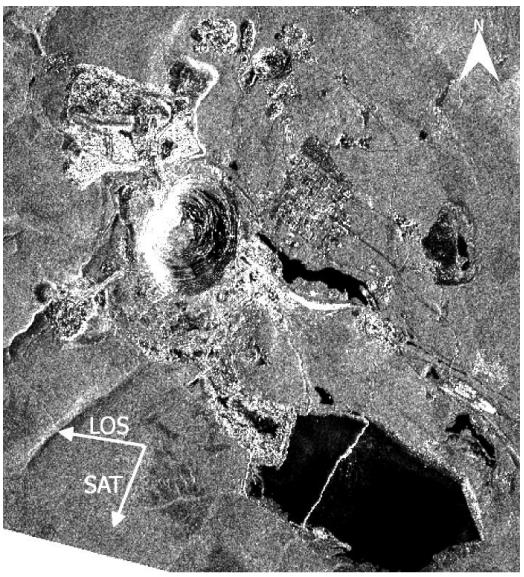
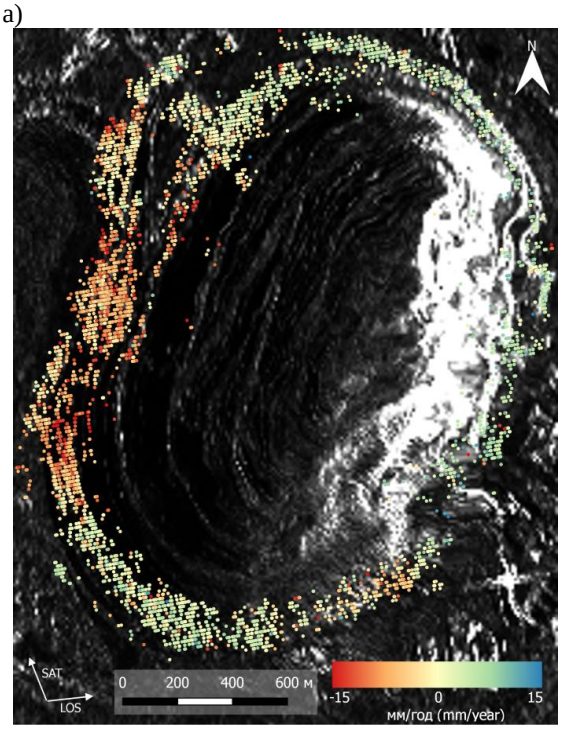


Figure 3: Amplitude radar space imagery for the ascending (a) and descending (b) orbits of Sentinel-1A (Filatov et al, 2017).

Based on the interpretation of radar satellite images were designed digital 3D maps of displacements (Figure 5) and simulated virtual observation sites at the monitored mining sites (Figure 6).

Within the boundaries of the testing sites regular in-situ surveying and geodetic measurements are carried out. Displacement plots (measurement step 0.1 ÷ 10 mm), reflecting their development during the observation period, are built on the profile of the virtual testing sites.

a)



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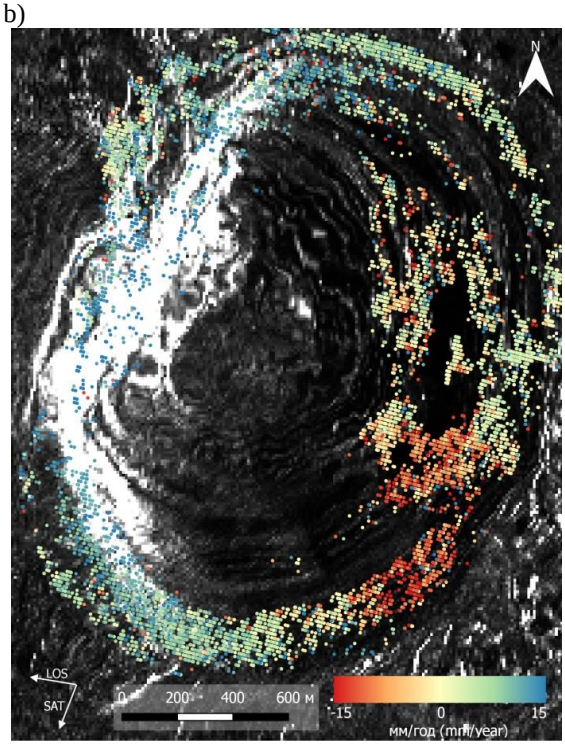

Figure 4: The velocities of the reflector points'displacements on the mining object for the ascending (a) and descending (b) orbits of the space images (Filatov et al, 2017).

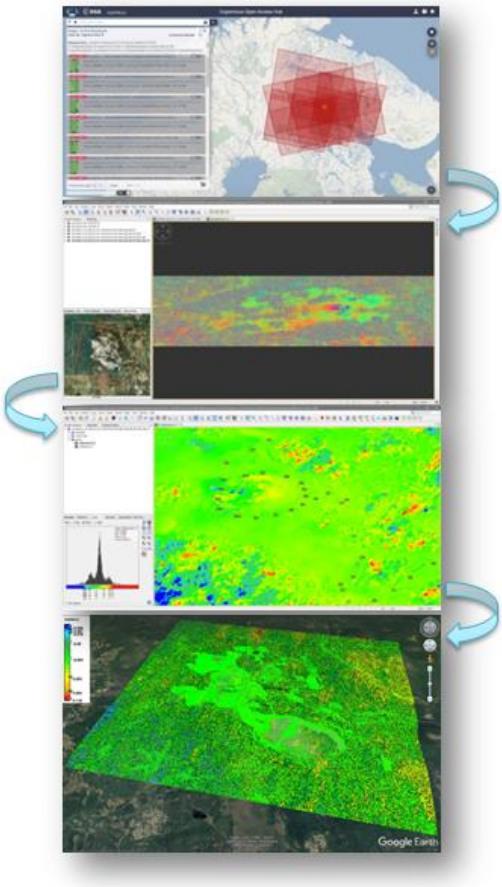

Figure 5: Design of a multiscale 3D map of the Earth's surface displacements based on the processing of radar satellite images (Melikhov and Kalashnik, 2023).

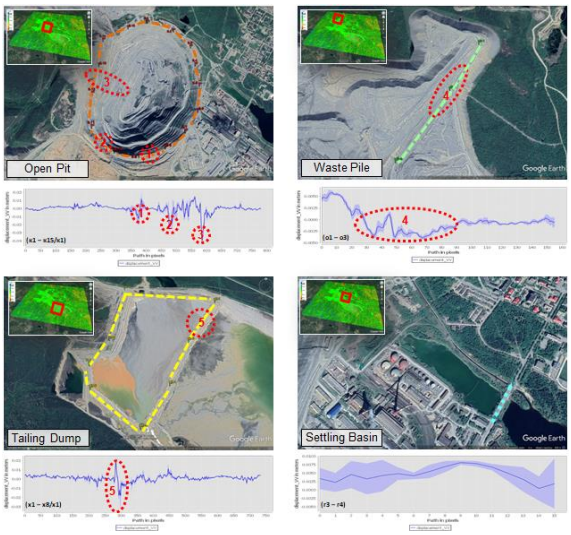

Figure 6: Organization of a virtual system for deformation monitoring of the Earth's surface displacements based on radar imaging of the mining territory (Melikhov and Kalashnik, 2023).

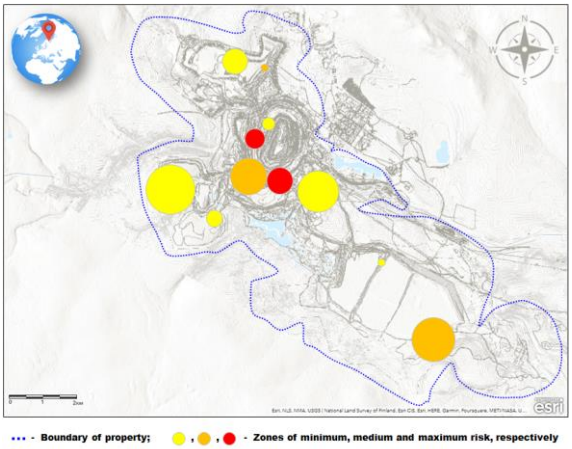

Figure 7: Interactive multiscale map of potential geological risks with hazard classification based on space and digital technologies (Melikhov and Kalashnik, 2023).

Interactive visualization of natural and technogenic hazards on the multiscale map or plan (Figure 7) allows improving the effectiveness of management decisions to minimize environment risks.

4 DISCUSSION OF RESULTS

Satellite data allows optimizing the location and operation of industrial monitoring systems in the supervision and control of the construction and operation of surface infrastructure. In the process of space imaging on a regular basis, it is possible to create digital databases of technogenic-modified territories for a group of deposits and multiscale maps of potential risks (Melikhov, 2022).

Space monitoring as part of an integrated observing system provides operational multi-scale data on environmental risks in controlled areas. Control and evaluation of the characteristics of the quality of satellite images and derivative information products determine the effectiveness of their use (Zemskov et al, 2018).The main techniques for their determination include special tests of spatial-frequency, spectral-radiometric and coordinate-measuring characteristics. As test objects, linearly extended elements or control reference points with known coordinates are selected. With remote sensing, it is possible to form separate zones beyond the visibility of spacecraft, which can affect the accuracy of measurements, especially in conditions of complex terrain and heavily built-up areas. Synchronization of types of surveys and spacecraft constellations in comparison with surface-based monitoring tools

makes it possible to increase the information content and reliability of the final data (Cigna et al, 2021).

The experience and results of the studies (Melikhov, 2021a; Melikhov, 2021b) provide a scientific-technical basis for the practical solution of the following tasks on protecting the environment of mining enterprises based on space monitoring:

- creation of digital 3D elevation models (DEM) based on stereo (amplitude analysis) or interferometric surveys (phase analysis);
- assessment of displacements and deformations of surface capital facilities and structures based on the construction of digital 3D maps (DEM) and graphs of displacements of the Earth's surface;
- mapping and inventory of deformations of surface mining facilities and structures and determination of accurate metric characteristics;
- calculation of the movement velocities of undermined surface objects based on the construction of route interferometry;
- mapping of mining facilities and structures based on the dielectric characteristics of reflective surfaces;
- zoning of the territory and ranking of risks according to the hazard degree;
- informing about emergencies and accidents;
- geoinformation support for solving tasks of industrial and environmental safety and environmental protection.

5 CONCLUSION

On the basis of the studies carried out, the authors have developed and justified a methodical approach to the multiscale assessment and management of environmental risks in the conditions of modern mining based on space and digital technologies. The method consists in scaling and combining satellite images from various types of spacecraft through visual and automated processing of spatial data using GIS and web-resources. One of the mining enterprises in the Barents Euro-Arctic region of Russia has become a scientific and technical basis for solving the tasks of areal predictive monitoring in ensuring industrial and environmental safety of mining facilities and territories.

Spatial zoning of the territory and categorization of risks for the environment according to the scale and hazard degree were carried out. Proposals were formulated on the practical application of space monitoring of mining areas for the environmental protection.

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