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Earth sciences

Monitoring of the earth's surface and mining facilities by radar interferometry

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ABSTRACT

Safe and efficient development of mineral deposits by underground method, occurring at great depths, is complicated by the fact that with an increase in the depth of mining, the nature of the course of deformation processes in the rock mass and the degree of their impact on the environment change significantly. Studies of deformation processes, their control and forecast in many cases determine the efficiency and safety of the development of deposits of solid minerals. A practical forecast can be made as a result of continuous tracking in space and time of deformation processes. This article presents modern satellite radars and their main characteristics. The features of the radar interferometry method are described, and the advantages and disadvantages of various methods of interferometric processing of radar images are considered. The experience of using space radar for monitoring mineral deposits in the Republic of Kazakhstan is analyzed. The question was raised about the possibility of intensifying the use of radar interferometry in the mining industry. Regular field observations are provided throughout the mining site, including hard-to-reach and dangerous areas, regardless of weather conditions. It is confirmed that the use of the radar interferometry method determines the displacement of the earth's surface with high accuracy. When using this method, data is received and processed remotely and generally does not require presence on the site. In addition, this article provides examples of successful application of the radar interferometry method in foreign countries at mining and oil facilities. Also, the use of radar interferometry allows you to quickly determine the zones of possible deformations of the earth's surface and organize high-precision surveying and geodetic observations in these zones. In this article, radar interferometry has been used to monitor the surface movement of the Annensky field with high accuracy since 2016 using Sentinel radar images, and as a result, a displacement map of the earth's surface has been generated.

Keywords: radar interferometry, radar sensing of the Earth, synthesized aperture radar, interferometric processing methods, radar sensors, surface deformation, mining industry.

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Introduction

Among the most important problems of monitoring the Earth's surface at mining facilities is the observation of hard-to-reach and dangerous areas with a high risk of Geodynamic phenomena. In this regard, non-contact monitoring methods, in particular space radar sensing, are actively used.

Radar shooting has its advantages in comparison with the classic methods of ground observation, laser scanning, aerial photography, space sensing in the optical range. A key point is the ability to conduct systematic field observations over the entire area of the object, including hard-to-reach and dangerous areas and regardless of weather conditions.

The use of the radar interferometry method makes it possible to determine the displacement of the Earth's surface with high accuracy. When using this method, data acquisition and processing is carried out remotely and in general does not require a presence at the object.

In recent years, radar sensing has been developing rapidly: the number of satellites, the quality and diversity of the received data is increasing, the technical characteristics of the shooting system and the methods of processing the received data are being improved, and new progressive software for processing data from satellite radar is constantly being updated and developed. In addition, the share of space radar data provided in free access is growing, which expands the possibilities of their use for scientific purposes. Successful scientific research, expansion of areas of implementation, improvement of processing technologies contribute to an increase in interest in the commercial use of these technologies [1].

Methods

Radar capture is an active method of sensing: the radar antenna emits a radio beam, and then, with the help of recording equipment, a reflected signal is obtained from the Earth's Surface [2]. Space radar sensing is carried out in the L-, C - and X-bands and provides the receipt of the necessary information in any weather conditions, regardless of the illumination of the surface, the state of the atmosphere. Radar shooting is carried out using a radar with a synthesized aperture (RSA). The use of radars with a synthesized aperture makes it possible to achieve a high spatial resolution in a wide review bar [3].

Currently, various radar sensor — projects of leading space agencies are working, among them: TerraSAR-X/TanDEM-X (DLR, Germany), Cosmo-SkyMED (ASI, Italy), Sentinel-1, T2 (ESA, European Space Agency), Radarsat-2 (MDA/CSA, Canada), ALOS-2 (JAXA, Japan), Kompsat-5 (KARI, Republic of Korea). In addition, there is a large amount of archived radar data from the satellites ERS, JERS, ENVISAT, RADARSAT-1, ALOS, etc. Currently, for example, New tandem-l shooting systems are being developed.

The radio waves used in the RSA differ in range, space resolution, width of the review bar, frequency of shooting, set of shooting modes (Table 1). These features must be taken into account when planning the study and selecting the initial data in accordance with the characteristics of the object under study.

Table 1 - The main characteristics of modern radar satellites

	TerraSAR-X TanDEM-X	Cosmo-SkyMED	Kompsat -5	Sentinel-1	Radarsat -2	ALOS-2
Radio Wave range	X	X	X	C	C	L
Wavelength (sm)	3.1	3.1	3.2	5.5	5.6	22.9
spatial resolution (m)	0.25—40	1—100	0.85—20	5—40	1—100	1—100

The method of radar interferometry

It uses the effect of electromagnetic wave interference to make measurements with radar interferometry. To do this, several coherent measurements of a certain area of the Earth's surface are carried out with a change in the position of the radar in Space [4]. Interferometric processing involves combining 2 different time PSA-images and creating an interferogram that allows you to measure the phase difference of two images, on the basis of which in the future the calculation of height marks and displacement will be performed [1]. Interferometric pairs of radar images are used as input data. The phase component is involved in processing, the amplitude of radar images is used in large-scale mapping [[4], [5]].

An important role is played by the characteristics of the initial images: spatial resolution, spatial and temporal basis, parameters of the orbit from which the data were obtained. These parameters determine the possibility of using images, in particular, the accuracy of detecting deformations and the scale of displacement maps obtained in Geodynamic, geomechanical monitoring.

Today, the term radar interferometry refers to various ways of processing radar images. When using the classical method of differential interferometry (DInSAR), the analysis of the Earth's surface displacement is carried out according to two capture cycles. If there is a Geodynamic, geomechanical observation of the Earth's surface, then the survey is carried out before and after the movements, respectively, and the analysis of the processes is limited to the period between the two surveys. A joint analysis of a series of radar images is more effective. For this, advanced processing methods are used — the small base distance method (Small Baseline — SBas) and the permanent reflector method (Persistent / Permanent Scatterers-PS). The SBas method uses interferograms with a minimal spatial basis, which helps to reduce geometric decorativeness. When using constant reflector interferometry, points are selected in the images that are constant reflectors of the radar signal, and this is used by them to analyze the phase change. Anthropogenic objects: buildings and structures, objects of the road network, bridges, etc. are often used as permanent sprinklers. In this regard, this method is most suitable for monitoring on built-in sites. Artificial angle reflectors are used for monitoring specific areas and objects [[1], [4], [6]].

Research results and their discussion

The main areas of use of this method in mining are the creation of digital models of the terrain and the calculation of the displacement of the Earth's surface. The problems of storage and visualization of the received information products are solved with the help of a temporary data model and Geoinformation technologies that ensure the correct presentation of monitoring data, their effective use, viewing of "historical" data [[7], [8], [9]].

Radar images are a source of information for solving the following problems in the mining industry:

- determination of deformation zones on the Earth's surface;
- control of subsidence and displacement of the Earth's surface in the cultivated areas;
- control of changes in buildings and structures;
- monitoring the stability of quarries, cemeteries and dump boards;
- monitoring the condition of hydro-reservoirs and tailings, including protective structures;
- monitoring the condition of mining transport equipment in quarries;
- environmental monitoring of reclaimed land.

Interferometric technologies, as well as amplitude information processing, are used to obtain hydrogeological characteristics of the area of deposits, in particular, to assess wetting [[10], [11], [12]]. Modern information on the state and level of groundwater allows for intensive and systematic, uniform development, with the exception of a sudden stop in the development process as a result of unexpected behavior of the Water Horizon [13].

Despite a number of successful projects in the field of radar interferometry [[14]], the use of radar technologies in Kazakhstan fields is currently limited, which is due to a number of factors. High-precision measurements are required to monitor mining facilities and infrastructure. To achieve the required accuracy, large spatial resolution data and the help of specialized software with a fairly high cost are required [15]. In addition, not all radar satellites provide the research frequency required for surface observation [[16]]. Analysis of vertical and horizontal shifts is possible in the presence of data from different orbits. Processing large series of radar images is a lengthy process and imposes hardware requirements, the necessary computing resources are not always available [17].

A significant part of the Earth's surface of Kazakhstan deposits is characterized by heterogeneity: the presence of snow cover, wetlands, seasonal changes in vegetation negatively affect the compatibility of the data obtained, limit the measurement period and the size of the images used.

There are different points of view on the need for additional measurements of the Earth when conducting radar observations of the Earth's surface. When using radar interferometry at Kazakhstani fields, it is usually necessary to carry out underground measurements: for a preliminary assessment of the possibilities of using radar surveys at a specific object, monitoring and checking the results, calculating absolute altitude values. For open-pit mines, the use of the sprinkler method involves the installation and control of additional artificial corner reflectors.

The determination of deformation of the Earth's surface depends on the capture parameters, the characteristics of the lower layer of the Earth's surface, the characteristics of the existing radar data, the availability of additional information products (reference DEM, etc.). The correct and realistic assessment of the determination of the displacement is still an undeveloped area. Due to all of the above factors, space radar is increasingly used to obtain a field idea of the dynamics of the Earth's surface and is used as an addition to classical methods to identify areas where high-precision monitoring is required.

Review of scientific research carried out using radar interferometry

As you know, natural and man-made displacement of the Earth's surface in the area of developing deposits is a potentially dangerous process, therefore, monitoring of the state of mining divisions by geodetic methods is provided, which, as a rule, requires significant costs and is not always carried out in the mode of operational monitoring. Currently, many mining companies have begun to use the radar interferometry method to measure the displacement of the Earth's surface with high accuracy, clarify the displacement values, promptly assess the situation and dynamics of processes, as well as predict their development.

An example of the successful application of the radar interferometry method is the case that occurred in 2007 on the territory of the city of Berezniki as a result of emergency flooding of a mine. The research was carried out by the Technical University of Claustal. The Department of SGGIS conducted independent studies of sedimentation processes in the territory of the city of Berezniki on the basis of satellite data from the Envisat spacecraft. In this area, very impressive data were obtained on the sedimentation detected in the period from 2007 to 2008, which corresponded to the actual processes of sedimentation (Figure 1), [18].

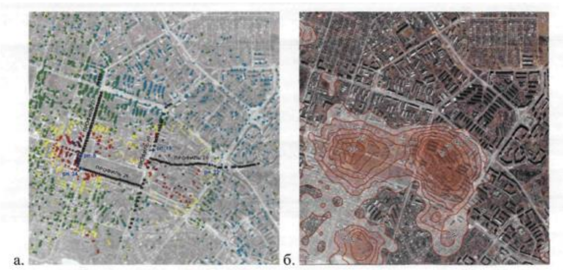

Figure 1 - (A) based on point interferometric analysis, the sedimentation area in the city of Berezniki and (B) the detected sedimentation is indicated by isoslines

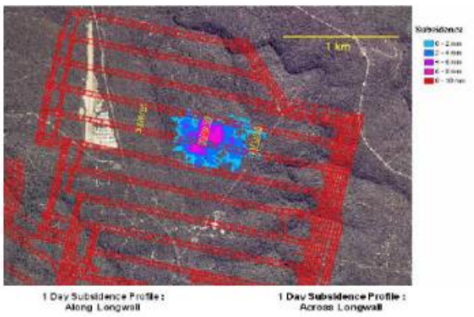

Figure 2 - Comparison of DInSAR interferogram with mine plan

Since 2007, Australia has been using satellite radar interferometry to monitor surface deformations of the Carmichael coal field located in new Wales. An interesting result was obtained using a tandem pair of ERS SAR. During the 24-hour period, the maximum amplitude of 1 cm shrinkage was determined by a resolution of 2 mm (see Figure 2). This was independently confirmed by the Geodetic service of the mining company. This example shows the possibility of temporary high-resolution (i.e. one-day) monitoring of the displacement of underground production using the DINSAR technique.

Since 2017, radar interferometry technology has been used at the Sishen field (South Africa) to monitor surface displacement based on data from the TerraSAR-X satellite. At the Sishen field, the area of dangerous subsidence was determined using radar interferometry. Due to the results obtained, work in this territory was suspended. The development of subsidence of the Earth's surface according to the results of radar interferometry is shown in Figure 3.

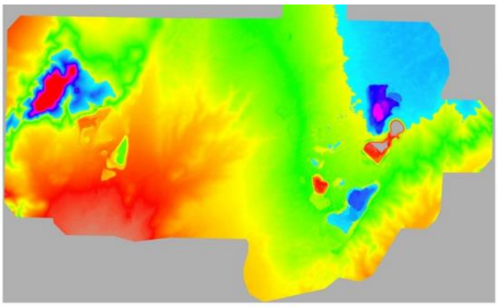

Figure 3 - Subsidence areas of the Earth's surface of the Sishen mine according to TerraSAR-X

Observation of the deformation of the Earth's surface of the Annensk field using radar interferometry:

The Zhezkazgan copper deposit is located in the central part of Kazakhstan, in the Kara-Kengir River Basin, in the south-east of the Ulytau mountains, in the west of the city of Zhezkazgan and the kengir reservoir, near the settlements of Satpayev. It includes the S mines and covers an area of 10 x 7 km. Active underground mining of the deposit has been carried out since the middle of the 20th century. Currently, the field is being developed by the Kazakhmys Corporation.

During the development period, a significant part of the reserves of the field was withdrawn. The field is mined by a chamber-column system. The empty excavated underground space is supported by pillar posts between tens of thousands of stones.

Of course, such a volume of underground cavities causes displacement and deformation of the Earth's surface and structures along the amplitude. Since the mid-1990s, individual settlement areas have been merged into larger areas that have been weakened. Underground and surface rock collapses began to occur, including leading to the destruction of buildings, structures, and infrastructure elements. Taking into account the location of settlements near the field (Satpayev. Rudnik, etc.), these processes pose a serious threat to human life.

In 2011, Kazakhmys Corporation organized monitoring of surface displacement at the entire site of the Zhezkazgan field using the methods of space radar interferometry conducted by the Russian company Sovzond [19].

The initial control was carried out on 17.01.11. During the observation period (9 months), the greatest subsidence of the Earth's surface was recorded at the combined mulda shift in the zone of Block 4-4yug along the Ann-4-I field of about 35 mm, at the Annensk field in the south-eastern part.

According to the results of observations, it was found that the rate of constant subsidence of the Earth's surface is on average 4 mm per month.

In accordance with the requirements of the" methodological guidelines for the identification of weakened sites and the operational assessment of the state of the excavated space in mines according to Zhezkazgan, 2011 " (Zhezkazgan, 2011), the Earth's surface is considered to be more than 35 mm of subsidence and sedimentation rate of more than 1 mm/month. The state of the mined space of block 4-4 south at the Ann-4-I field should be assessed as unstable.

Figure 4 shows the dynamics of the development of subsidence mulda from February to July 2012 according to the space radar interferometry.

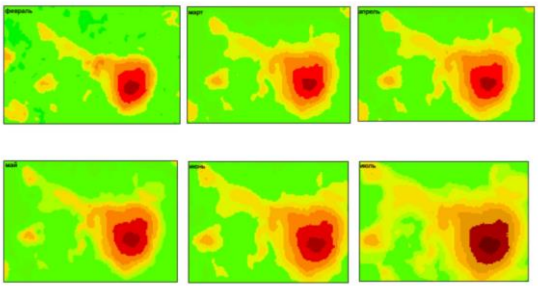

Figure 4 - Plan of subsidence of the Annensk field from February to July 2012

In addition, since 2016, with the help of Sentinel radar images, we have tracked the subsidence of the Earth's surface of the Annensk field. This scientific work was carried out at the Department of Surveying and geodesy of Satbayev University within the framework of the grant funding project "development of a system and methods for predicting the displacement of mountain mass in dangerous areas of the Earth's surface during subsoil development based on innovative methods of GIS technology" in 2018-2020. As a result of complex processing and interpretation of radar images, a vertical map of the Earth's surface displacement of the Annensky mine was obtained (Figure 5) [[20], [21]]. For a comparative analysis of the obtained interferometric data, the site where the control reps are located was selected. On this site, instrumental monitoring of surface deformations is carried out annually by the surveying service of Kazakhmys Corporation LLP. High-precision leveling is carried out along the profile lines, which are a network of soil and supporting rappers.

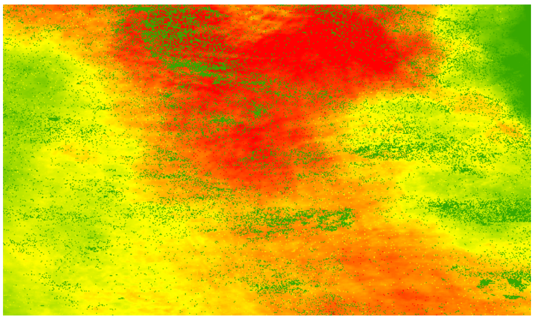

Figure 5 - Map of the Earth's surface displacement of the Annensk mine

We continued our research and continued monitoring the subsidence of the Annensk field surface using Sentinel radar images from 2021 to 2023 (Fig. 6).

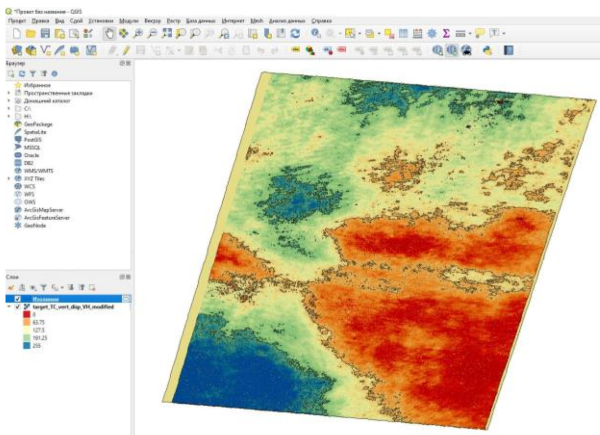

Figure 6 - Earth's surface shift map of the Annensk field obtained using Sentinel radar images

The study, conducted between 2021 and 2023, showed that due to the heating of the Annenskoye field, there are deposits characteristic of the Central and South-Eastern parts of the earth's surface. At the same time, the maximum absolute value of the subsidence of the earth's surface within the shrinkage of the Annenskoye field was 0.8 cm

For a more complete and detailed assessment of deformations in the deposit area, it is necessary to analyze monthly mining plans and space data. During the research, some areas were processed and secured, which made them inaccessible for the corresponding analysis.

This feature of the processes of collapse and displacement of rocks in the real conditions of the Annensk highlands leads to the following practical conclusions:

- Mining operations in the collapse zone are permitted only after the process of displacement and stabilization of the geomechanical environment has been completed, which can be determined by comprehensive observation of the massif. Based on the results of visual observations of the state of mining operations and the development of manifestations of rock pressure, simple beacons, signs, gates, as well as the weakening of the seismic activity of the massif and the shift of the earth's surface;
- for further monitoring of the development of rock deformations it is necessary to continue geomechanical monitoring based on an expanded model of geomechanical monitoring of the territory of the Annensky mine using topographic and geodetic methods and space radar interferometry technologies;
- Use permanent reflector techniques to improve the accuracy of geomechanical observations using space radar interferometry technologies.

Conclusion

Space radar interferometry is an important part of an integrated system for monitoring the condition and creating a continuous situational map of deformations on the earth's surface. We chose to use Sentinel spacecraft data and SAR interferometry methods to monitor the drift of the Annensk field's earth's surface.

To properly use SAR interferometry methods, it is necessary to use a tandem pair of radar satellite images with a minimum value of the perpendicular baseline (the distance between the spacecraft) and a minimum consistency value to determine the absolute values of the Earth's surface displacement generated during the studied period of time. To apply SAR interferometry methods, a coherent analysis of tandem pairs of radar satellite images was carried out to determine their optimal parameters.

As a result of the work carried out, a land management map of the Annensk mine territory was compiled. In addition, the maximum absolute value of the subsidence of the earth's surface within the subsidence of the Annenskoye deposit was 0.8 cm. Shifts occurred both in the direction of increase during the formation of rock dumps, and in the direction of decrease as a result of subsidence of the earth's surface.

The obtained results have proven that they correspond to the data of radar interferometry, conducted by surface measurements, as well as by the limited liability company "Sovzond".

Thus, radar technologies have great potential, their use in the mining industry is very promising. This is facilitated by the development and improvement of technologies for obtaining and processing radar data. Also, the use of radar interferometry allows you to quickly determine the zones of possible deformations of the earth's surface and organize high-precision mine surveying and geodetic observations in these zones.

Conflict of interest. On behalf of all authors, we declare that there is no conflict of interest.

Credit statement of the authors: **A. Altayeva:** processing of space data, writing of the article; **B.Sadykov:** analysis and processing of space data; **A.Umirbaeva:** performing a review of domestic and foreign information; **A. Dastan:** performing a translation of the article summary.

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Радарлық интерферометрия әдісінің көмегімен жер беті мен тау-кен нысандарын бақылау

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ТҮЙІНДЕМЕ
Үлкен тереңдікте орналасқан пайдалы қазбалардың кен орындарын жерасты әдістерімен қауіпсіз және тиімді игеру тау-кен жұмыстарын жүргізу тереңдігінің ұлғаюымен тау-кен массасындағы деформация процестерінің сипаты мен олардың қоршаған ортаға әсер ету дәрежесінің айтарлықтай өзгеруімен қиындайды. Деформациялық процестерді зерттеу, оларды бақылау және болжау көп жағдайда қатты пайдалы қазбалардың кен орындарын игерудің тиімділігі мен қауіпсіздігін анықтайды. Деформация процестерін кеңістікте және уақыт аралығында үздіксіз бақылау нәтижесінде практикалық болжам жасауға болады. Бұл мақалада қазіргі заманғы спутниктік радарлар және олардың негізгі сипаттамалары ұсынылған. Радиолокациялық интерферометрия әдісінің ерекшеліктері сипатталып, радиолокациялық кескіндерді интерферометриялық өңдеудің әртүрлі әдістерінің артықшылықтары мен кемшіліктері қарастырылады. Қазақстан Республикасындағы пайдалы қазбалар кен орындарын бақылау үшін ғарыштық радиолокацияны қолдану тәжірибесі талданды. Тау-кен өнеркәсібінде радиолокациялық интерферометрия әдісін қолдануды жандандыру мүмкіндігі туралы мәселе көтерілді. Тау-кен кешенінің бүкіл аумағында, оның ішінде жетуі қиын және қауіпті аймақтарда, ауа райы жағдайларына қарамастан тұрақты далалық бақылаулар жүргізуге болатындығы дәлелденді. Радар интерферометриясы әдісін қолдану нәтижесінде жер бетінің жылжуын жоғары дәлдікпен анықтауға болатыны расталды. Бұл әдісті қолданғанда деректерді алу және өңдеу қашықтықтан жүргізіледі және жалпы жағдайда объектіде болуды талап етпейді. Сонымен қатар, бұл мақалада шет елдерде радар интерферометрия әдісін тау-кен, мұнай объектілерінде сәтті қолданудың мысалдары келтірілген. Сондай-ақ, радар интерферометриясын қолдану жер бетінің мүмкін болатын деформация аймақтарын жедел анықтауға және осы аймақтарда дәлдігі жоғары маркшейдерлік-геодезиялық бақылауларды ұйымдастыруға мүмкіндік береді. Бұл мақалада 2016 жылғы Sentinel радиолокациялық суреттерін және радиолокациялық интерферометрия әдісін пайдалана отырып, Анненское кен орнының жер бетіндегі жылжулары жоғары дәлдікпен анықталып, орын ауыстыру картасы жасалды.

Түйін сөздер: радар интерферометриясы, жерді радиолокациялық зондтау, синтезделген апертурлық радиолокатор, интерферометрлік өңдеу әдістері, радар сенсорлары, жер бетінің деформациясы, тау-кен өнеркәсібі.

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Мониторинг земной поверхности и горнодобывающих объектов методом радарной интерферометрии

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АННОТАЦИЯ
Безопасное и эффективное освоение месторождений полезных ископаемых подземным способом, залегающих на больших глубинах, осложняется тем, что с увеличением глубины ведения горных работ существенно изменяется характер протекания деформационных процессов в массиве пород и степень их влияния на окружающую среду. Исследования деформационных процессов, их контроль и прогноз определяют во многих случаях эффективность и безопасность разработки месторождений твердых полезных ископаемых. Практический прогноз может быть осуществлен в результате непрерывного слежения в пространстве и во времени за деформационными процессами. В данной статье представлены современные спутниковые радары и их основные характеристики. Описаны особенности метода радиолокационной интерферометрии, рассмотрены преимущества и недостатки различных методов интерферометрической обработки радиолокационных изображений. Проанализирован опыт использования космической радиолокации в целях мониторинга месторождений полезных ископаемых в Республике Казахстан. Был поднят вопрос о возможности интенсификации применения метода радиолокационной интерферометрии в горнодобывающей отрасли. Доказана возможность проведения регулярных полевых наблюдений на всей территории горнорудного комплекса, включая труднодоступные и опасные участки, независимо от погодных условий. Подтверждено, что применение метода радиолокационной интерферометрии определяет смещение земной поверхности с высокой точностью. При использовании этого метода получение и обработка данных производится дистанционно и в общем случае не требует присутствия на объекте. Кроме того, в данной статье приведены примеры успешного применения метода радиолокационной интерферометрии в зарубежных странах на горных, нефтяных объектах. Также применение радиолокационной интерферометрии позволяет оперативно определять зоны возможных деформаций земной поверхности и организовывать высокоточные маркшейдерско-геодезические наблюдения в этих зонах. В данной статье, используя радарные снимки Sentinel от 2016 года и метод радарной интерферометрии были определены сдвижения земной поверхности Анненского месторождения с высокой точностью и построена карта смещения.

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