Technologies for obtaining and processing of space radar images for monitoring the state of the Earth's surface

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Abstract. The paper presents the main results of the analysis of the efficiency and suitability of satellite differential radar interferometry methods using free software products and satellite imagery for general purposes. The work used data from the Copernicus program of the European Aerospace Agency; processing was carried out for radar images of the Sentinel-1 satellite family. The result of the research is a series of recommendations on the use of the considered technology and the possibility of its implementation in enterprises, taking into account the revealed features, advantages and disadvantages.

1. Introduction
The technological progress of the 21st century has allowed humankind significantly advancing in the fields of obtaining data about the surrounding environment. New methods for performing measurements and their subsequent processing gave engineers the opportunity to bring the branch of science related to ecology, construction, and development of mineral deposits to a radically new level [1]. However, the apparent simplicity of applying new technologies that required the highest level of knowledge in the fields of engineering and computer technology, as well as the use of equipment that was very expensive at the time of implementation, led to unexpectedly high costs in their application. The use of such technologies was possible only by a team of high-level scientific engineers supported by large investments. Thus, such technologies as laser scanning, radar interferometry and automated photogrammetry have been applied and studied only in highly specialized companies. This fact slowed the birth of new ideas for their application and development. Currently, there are organizations whose activities are aimed at popularization of modern technologies of any kind [2, 3]. The ability to learn such techniques by ordinary users allows finding new areas of application and is beneficial to the scientific community. This work examines the possibility of radar interferometry implementation for monitoring the position of the earth’s surface. Observation of deformations during the development of oil fields, the study of the effects of technological processes on surface movement can be attributed to possible areas of technology application [4].

2. Materials and methods
Currently, the technique of land subsidence monitoring using satellite radar imagery is not a new technology and is used in many mining companies. The evaluation of the effectiveness of radar interferometry products designed for ordinary users was the main objective of this study.

There are several methods for obtaining data on the position of the earth's surface using interferometry. The synthesized aperture improves spatial resolution, which varies from 1 m to several
tens of meters depending on the system [2]. The satellite performs continuous scanning of the earth's surface by a radar with a certain capture width (usually of several tens of kilometers on the surface) during the satellite's movement along orbit. Scan data usually consists of phase and amplitude information for each pixel. If there is direct or indirect data on the satellite's position during the scanning process (orbit configuration relative to the surface of a certain level), an antenna tens or hundreds of kilometers wide (synthesized aperture radar, SAR) can be synthesized. Thus, a SAR image is a set of complex heterogeneous data, including the phase and amplitude of the returned signal, (possibly) orbit data, time data, and image geometry. Using this data it is possible to perform a visual assessment of the image based on the amplitude, but the phase value of the returned signal is not sufficient to estimate the position of the point relative to the geoid surface. In addition to the phase difference value of the outgoing and returned signal relative to the earth's coordinate system, data on the exact number of integer phases is required. The problem of phase ambiguity can be solved by processing using a pair of images of the same area, obtained from two close parallel orbits (fig. 1).

Two images are used either from different satellites, or from one satellite for different time periods. The set of images is limited by their coherence - a value expressed by spatial and temporal decorrelation. The satellite line of sight (LOS) is rarely set vertically, there is always a scanning angle \( \alpha \). Spatial decorrelation is caused by the difference in angles \( \alpha_1 \) and \( \alpha_2 \) between vertical line and LOS from satellite to the same object that appears due to the deviation of satellite positions in space at the time of scanning. The spatial decorrelation value is shown as the length of the spatial baseline \( B \), which is divided into parallel \( B_{par} \) and perpendicular \( B_{perp} \) components of the direction of motion of the satellite. The perpendicular component is of primary importance, its boundary value, which characterizes the possibility of using a pair of images, depends on the wavelength and spatial resolution of the system and is usually embedded in software complexes. Temporary decorrelation represents all changes that occur between scanning operations. Large-scale changes in the position of the earth's surface, the appearance of precipitation in the form of ice and snow, changes in the properties of the atmosphere affect the overall processing and reduce the coherence of images. Temporary decorrelation is the time interval between two images, the boundary value is individual for each object and can be precisely determined only during processing. The standard processing algorithm consists of several steps that require the use of specialized software systems [5, 6]. First, the geometry of the images is recorded: the images must be combined so that each pixel of one image corresponds to the pixel of another image, and both pixels correspond to the same point on the ground. This step requires satellite orbit data for geocoding. Image data typically includes the amplitude and phase of the signal as the real and imaginary parts of a complex number. The result of pointwise multiplication of these pair of images is a new image with a difference of phase components in each pixel - this product is called a complex differential interferogram. The values of the phase change in
the interferogram consists of 3 elements:

\[ \Delta \varphi = \Delta \varphi_{\text{topo}} + \Delta \varphi_{\text{def}} + \Delta \varphi_{\text{e}} \]  

\( \Delta \varphi_{\text{topo}} \) - phase difference obtained by radar scanning of one surface area from two different satellite positions

\( \Delta \varphi_{\text{def}} \) - phase difference obtained by changing the position of the object between satellite measurements

\( \Delta \varphi_{\text{e}} \) - excess phase difference due to atmospheric and other noise and refraction of the signal

If a pair of images was obtained from one position, there will be no spatial baseline and the difference between the two angles \( \alpha \) will be equal to 0, then the interferogram loses the relief component and will only show the surface displacement. There are reliable noise filtering algorithms (Goldstein) to minimize the value of excess phase difference \( \Delta \varphi_{\text{e}} \). Further actions depend on the needs of the user. When the determination of subsidence values is required, the topographic component of the phase \( \Delta \varphi_{\text{topo}} \) can be extracted from the resulting product, if not - \( \Delta \varphi_{\text{topo}} \) can be included in a digital elevation model calculation. In any case, a flat interferogram containing the required values of the phase difference is unwrapped using special algorithms - interpolating the results through over 0 and 2\( \pi \) phase values gives a continuous map of heights or deformations.

As it is mentioned above, this technology has long been available only to large companies that have the opportunity to access and process satellite data [7]. This type of work was performed relatively rarely, as it required a very long preparation and was difficult to carry out. The situation began to change with the founding of the Copernicus program. The program was launched in 2008 by the European Aerospace Agency; in 2014 Copernicus started fully operational services. The main mission of the program is to obtain complete comprehensive information about the surface, hydrosphere, biosphere and atmosphere of the Earth. According to the main idea of the program, the received information is distributed free of charge to any users. Copernicus is represented by a family of six satellite blocks called Sentinels. The Sentinel-1 satellite pair, the first of which was launched on April 3, 2014, is the most important in terms of obtaining information about the earth's surface. These satellites carry a C-band synthetic aperture radar with 5 cm wavelength specially manufactured for SAR interferometry. Two satellites are moving in Sun-synchronous near-polar orbits with repeat cycle of 12 days, which gives the opportunity to obtain a radar image of any territory with an interval of 6 days. Sentinel-1 can produce Interferometric Wide-Swath image with 5 m resolution and 240 km swath. All processing can be performed in the SNAP software package (all images and software are distributed free of charge). Theoretically, the characteristics of this complex meet the requirements for preliminary operations while surveying of open pit mines and observing technogenic deformations of the earth's surface [8, 9].

3. Image processing

The assessment of changes in image coherence was the first stage of the study. Downloading images from the Copernicus program for a selected object involves automated sorting of products with an overlap of 100%, so the spatial base does not exceed the optimal values. Thus, the time base has the greatest effect on coherence in this case. Coherence can be estimated for each pixel on a scale of 0 to 1 after loading and preprocessing. In total, 110 images were analyzed for 13 objects in various combinations for different time periods from 12 days to 1 year (table 1). A large number of images in some groups is caused by their use for evaluating the effectiveness of automatic point search methods (points with constant signal reflection and relatively small values of position change between images – “Stanford Method for Persistent Scatterers”, STAMPS).

Visual estimation of coherence does not give an absolutely reliable result, but allows preliminarily evaluating the effectiveness of working with a pair of images. In some cases, a successful processing result may not be possible even with a minimum time interval.
Table 1. Radar images count

| №  | Object / location                                           | Period                      | Number of images tested |
|----|------------------------------------------------------------|-----------------------------|-------------------------|
| 1  | Korkinskiy open-pit mine (Russia)                          | June – July 2017             | 6                       |
| 2  | Belchatów open-pit mine (Poland)                           | August 2017                  | 2                       |
| 3  | Tagebau Welzow-Süd open-pit mine (Germany)                 | April – September 2018       | 10                      |
| 4  | Bingham Canyon Mine (USA)                                  | May – August 2018            | 6                       |
| 5  | Hambach surface mine (Germany)                             | May – September 2017         | 8                       |
| 6  | Kovdor mining and processing (Russia)                      | June – August 2018           | 9                       |
| 7  | United Kirovskiy mine (Apatit, PhosAgro) (Russia)          | June – August 2018           | 5                       |
| 8  | Thompson Creek Mine (USA)                                  | July – September 2018        | 6                       |
| 9  | Borodinskiy open-pit mine (Russia)                         | August 2018                  | 2                       |
| 10 | Hokkaido Eastern Iburi earthquake (Japan)                  | September 2018               | 4                       |
| 11 | Kumtor open-pit mine landslide (Kyrgyzstan)                | November – December 2019    | 2                       |
| 12 | Gazprom Astrakhan (Russia)                                 | January 2019 – January 2020 | 17                      |
| 13 | Mexico city center (Mexico)                                | January 2019 – January 2020 | 22                      |

The value of coherence affects the quality of the interferogram; it can be estimated visually using coherence pictures. High (close to 1) coherence values are indicated in white color; a smooth and less noisy interferogram will be obtained with large amount of white areas of the coherence layer. Figure 2 shows the coherence estimation and unfiltered interferogram for Thompson Creek Mine: the left column shows results for 48-days image pair, the right – 12-days pair. With a short time base the interferogram becomes less noisy. In the first time the average coherence is 0.373, but a short time base gives a coherence of 0.513.

The study of the images presented in the table showed that in 70% of cases acceptable coherence values for the main part of the image area are achieved at time intervals of 12 to 40 days. This indicates a drawback of this system: if the task of monitoring deformations is set, the recommended period for one pair of images should not exceed 1 month [10].

After the coherence estimation, appropriate pairs were processed to prove the possibility of using the method in mining engineering. As it is noted above, the amplitude layer allows a visual assessment of the object in the image.
Figure 2. Coherence estimation results: a – coherence visualisation, b – coherence plot, c – resulting interferogram

Figure 3. Open-pit sites position: a – amplitude image, b, c – amplitude image ground set, d – deformation layer ground set

Figure 3 – a, b, c shows the resolution of the image which is sufficient to monitor the position of the sides of the Belchatów open-pit mine and even the position of large slowly moving equipment (rotary excavators are visible in the image a). The benches of the quarry on August 03, 2017 are marked in yellow, the benches on August 27, 2017 are marked in red. Further processing with the extraction of the topographic phase showed that obtaining information about a quarry subsidence is technically possible. The extraction sites often have low coherence, which reduces the efficiency of rock mass volume monitoring. At the same time, Figure 3c shows areas requiring special attention in order to verify the activation of the subsidence process.

4. Conclusion
The method of radar interferometry with free custom products does not have sufficient accuracy and reliability to completely replace the classical measurement methods. At the same time, the method has a number of advantages, which include:
- almost complete absence of need for costs and investments
- software products are clear, easy to learn and do not require long and expensive training or the
use of third-party companies for processing
- raw satellite data is available to any users via the internet at any time without pre-orders and arrangements
- there is full accessibility of the entire area of the globe, with the exception of the circumpolar zones, taking into account the features of the orbit of the Sentinel satellites
- the availability of data on the position of the relief over large areas

The considered technique can be implemented for a preliminary assessment of the need for further use of more reliable and expensive, but less operational and simple technologies.

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