Calculation of vertical displacement of the earth surface in the “Vostochny” open pit using radar data

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Abstract

The paper deals with the issues of assessment of the condition and changes in the land surface on the territory of the Vostochny open pit (Kemerovo region). The application of the multi-pass series of Sentinel-1 satellite radar data using the Small Baseline Subset (SBaS) method to determine the Earth surface displacement dynamics using constructed vertical displacement maps is demonstrated.

Keywords

Radar data, Vostochny open pit, Small Baseline Subset, Sentinel-1, earth’s surface deformations.

1. Introduction

Currently Kuzbass is one of the largest mining regions in Russia. The high technogenic load associated with the annual increase in the volume of coal mining leads to a redistribution of the stress-strain state of significant volumes of rock mass with adverse consequences for the environment [1]. Deformations of the earth’s surface in such regions, resulting from uneven subsidence and horizontal displacements of rocks, reach large areas and are a source of emergency situations, which, in turn, can harm not only the environment and the operating mode of the enterprise, but also human lives.

At the Vostochny open-pit mine, active open-cut coal mining has been carried out for 10 years. For example, in 2010, 950 thousand tons of coal were mined, and in 2018 — already 4.3 million tons [2]. Such intensive mining has a direct impact on the relief, therefore, to prevent emergencies, it is necessary to monitor the state of the earth’s surface.

2. Methods for processing satellite radar data

Today, satellite radar data are actively used to determine the deformations of the earth’s surface. Their advantage lies in the relatively low price per square kilometer, as well as the independence of shooting from weather conditions and time of day. To process such data, 3 main methods have been developed:

- differential interferometry (DinSAR). Used to process two images;
- method of persistent scatterer (PS). It is used for point estimation of deformations based on a multi-pass series of images;

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— small baseline subset (SBaS). Used for areal strain assessment based on a multi-pass series of images.

The principle of radar interferometry is as follows. Each pixel of a satellite image contains information about the real and imaginary parts of the wave reflected from a section of the earth's surface and received by the satellite. Thus, a satellite image has two components: real and imaginary parts, which can be converted into amplitude (brightness) and phase components of the image. Note that the typical size of the earth's surface in one pixel of the image exceeds a square meter, which makes it impossible to determine the millimeter offsets from the brightness component of the image. For this purpose, the analysis of the phase components of the set of images is used.

Based on the set of phase components of SAR images obtained by the satellite at different points in time (with a periodicity, for example, one image per day), the change in the phase component over time is calculated. The change in the phase component is associated with a linear relationship with the path difference of the wave reflected from the surface and, thus, it becomes possible to measure the vertical displacements of objects on the earth's surface, comparable to the satellite signal wavelength, which is of the order of several centimeters [3].

The main difference between the methods is the amount of initial data for processing. For example, the differential interferometry method uses a pair of radar images taken with a short time interval (from several days to a couple of weeks). As a result, we get a map of the displacements of the earth's surface, which occurred during the period between surveys. SBaS requires at least three images and PS requires at least thirty. The last two methods make it possible to assess the dynamics of changes in the earth's surface over a long period of time (from several months to several years). Let's consider all these methods in more detail.

Differential interferometry is a classic pairwise method for calculating areal displacements. It includes the following stages: formation of an interferogram, filtering and calculation of coherence, phase sweep, correction and refinement of orbits, recalculation of phase into displacements. At the output, we get a map of displacements of the earth's surface.

PS (Persistent Scatterers) method — calculation of displacements of point targets, which are permanent reflectors for a radar satellite. Allows you to measure detailed displacements on infrastructure objects. It is used, as a rule, for areas with urban areas. Includes the same steps as the SBaS method. At the output, we also get a map of the average rates of change in surface displacements.

SBaS (Small Baseline subset) method — calculates accurate areal displacements using a series of satellite images with small baselines. It includes the following stages: formation of an interferogram with subsequent filtering and sweeping, correction of orbital errors, first inversion, second inversion (atmospheric correction) and orthorectification, geocoding of processing results. The output is a point vector file, which is a map of the average rates of change in the displacements of the earth's surface [3, 4].

3. Results and conclusions

In our work, we used the latter method, since it allows us to reveal the dynamics of areal deformations of the earth's surface over a long period of time.

The territory of the Vostochny open-cut mine was chosen as the object of research. For calculations, 32 radar images from the Sentinel-1B spacecraft were selected for the period from 09/10/2019 to 10/27/2020. with a shooting frequency of 12 days. This spacecraft performs imaging in the C-band with a resolution of 5×20 m/pixel (in the Interferometric Wide Swath mode) and with VV and VH wave polarizations.

Typically, the initial radar image covers a large area (several tens of thousands of square kilometers), therefore, in order to reduce processing time, a separate area of interest with an area of about 15 square kilometers was allocated to the territory of the Vostochny mine. To reduce the volume of temporary and intermediate processing data, images with VV polarization were used. In addition, it has been experimentally established that such polarization is better suited for determining displacements than VH. All processing was carried out in the developed software package within the framework of the RFBR project. The scheme for calculating the displacements by the small baseline subset method is shown in Figure 1, and the description of the procedures in Table 1. The SRTM digital elevation model was used for more accurate core registration of radar images.

At the first stage, combinations of pairs of images (master image — auxiliary image) are determined, which are used to form several differential interferograms.

It should be noted that those pairs of images that do not exceed the baseline threshold value are suitable for processing (the default value is 100%). If the value is exceeded, then the pairs are excluded from further processing.

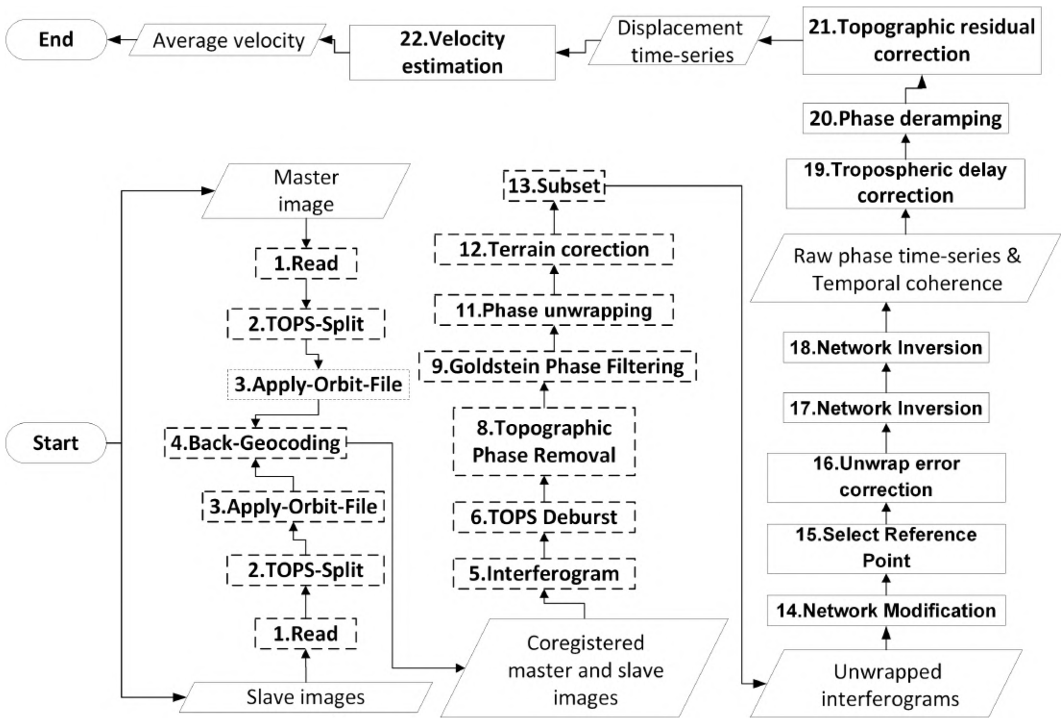

Figure 1: Complete scheme for calculating displacements using the SBaS — preliminary processing steps are highlighted with a dotted line.

Table 1
Description of SBaS preprocessing procedures for radar data.

Procedure name	Contents of the procedure	Number of images Input	Number of images Output
TOPS Split	Extract subbands (burst) from a selected swath (swath) of a survey in an image.	1	1
Apply-Orbit-File	Updating orbit state vectors in image metadata.	1	1
Back-Geocoding	Correlation of two images (master and slave) in the same strip using orbital metadata and digital elevation model (DEM).	2	1
Interferogram	Calculation of the folded phase of an interferogram by pointwise complex multiplication of two images corrected for the reference phase using an interpolation polynomial of the 2$^{\text{nd}}$ degree	2	1
TOPS Deburst	Combining contiguous sub-bands in the direction of the shooting range (range) and in the direction of the azimuth (azimuth).	1	1
Topographic Phase Removal	The procedure performs "smoothing" of the interferogram by removing the topographic phase. The procedure simulates (forms in the RAM) an interferogram based on a reference elevation matrix (DEM) and subtracts it pixel by pixel from the original interferogram.	1	1
Goldstein Phase Filtering	Phase filtering to reduce phase residuals and improve unwrapped phase accuracy using Goldstein's nonlinear adaptive algorithm.	1	1
Phase Unwrapping	2D phase unwrapping — recovering the absolute phase values from a 2D array of baseline phase values using the least cost flow method.	1	1
Subset	Selecting a sub-area of an image.	1	1
Terrain Correction	The procedure is designed to correct geometric distortions (location of each pixel) of the image using a digital elevation model. These distortions are caused by the "side effect of the geometry of the survey", which appears due to the installation of the radar perpendicular to the direction of flight. These are the so-called topographic distortions, which do not allow correctly displaying the obtained images in geographic coordinate systems, for example, on an electronic map.	1	1

Then, standard interferometric processing was performed with core registration, filtration, and phase unfolding of the pairs of images selected at the first stage. For core registration of images, incoherent accumulation parameters were used equal to 1 in azimuth and 5 in range. To improve the accuracy, an SRTM v4 digital elevation model was used with a spatial resolution of about 30 meters (1 arc second). The noise was filtered using the Goldstein filter. After that, the procedure for correcting the phase incursion from the Earth's ellipsoid [5] was performed, at which the topographic phase was removed from the obtained interferograms. The next step is two stages of inversion. The first step is to determine the resulting height and displacement rate. On the second, date offsets are obtained, which are filtered to remove atmospheric phase components. Finally, the results are geocoded, filtered by velocity and altitude to remove areas with high noise readings (areas with rich vegetation).

During the processing of the initial images by the SBaS method, a map of the average rates of change in the vertical displacements of the earth's surface was built (Figure 2). This map is a vector file with 11861 points. Each point contains a set of attributes, such as geographic coordinates, average displacement rate value, and so on. Points with negative vertical displacements are highlighted in blue, which indicate subsidence of the earth's surface, and in red, elevations of the earth's surface.

To connect the obtained results with real terrain, we used a digital terrain model (DTM) built on the basis of UAV data, dated October 21, 2019 (Figure 3). Further, in the QGIS program, the resulting map of average rates of change in displacements was superimposed on this DTM (Figure 4). Figure 3 shows that most of the displacements are recorded on the dumps of the Vostochny open-pit mine. The elevations of the earth's surface are recorded in the northwestern

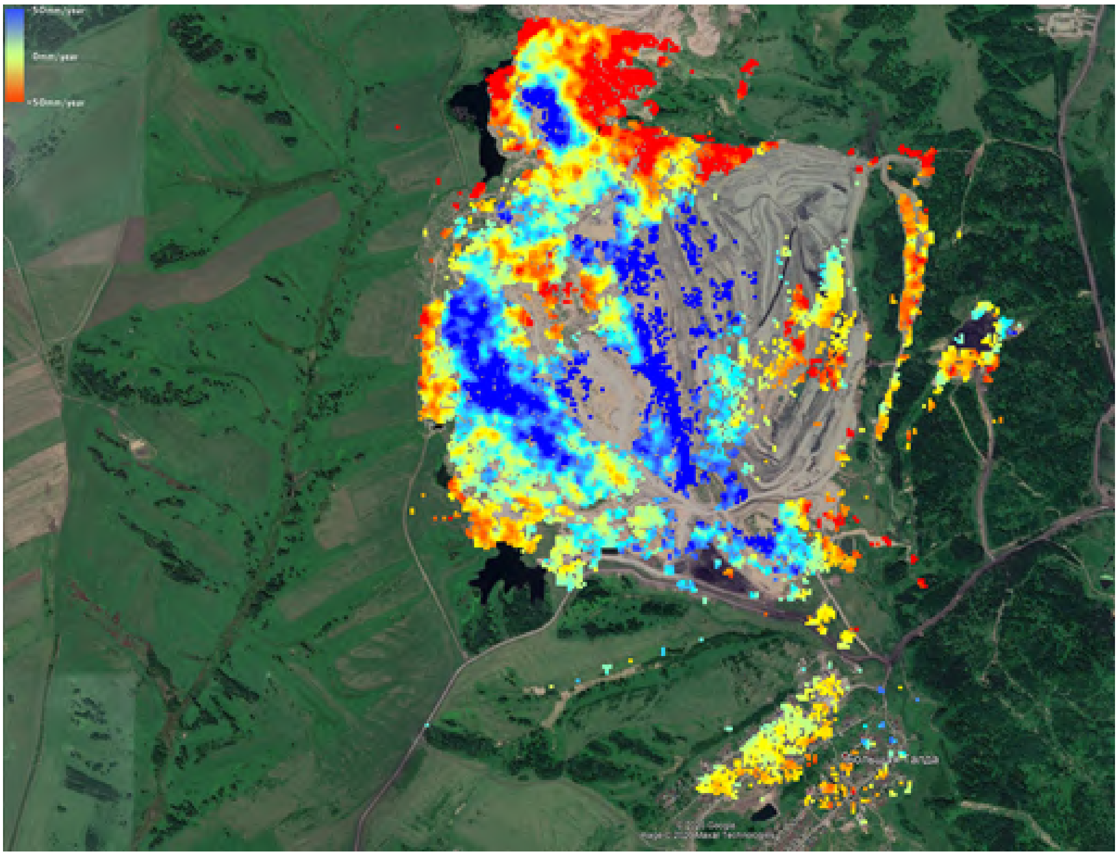

Figure 2: Map of average rates of change in vertical displacements. Google Maps background.

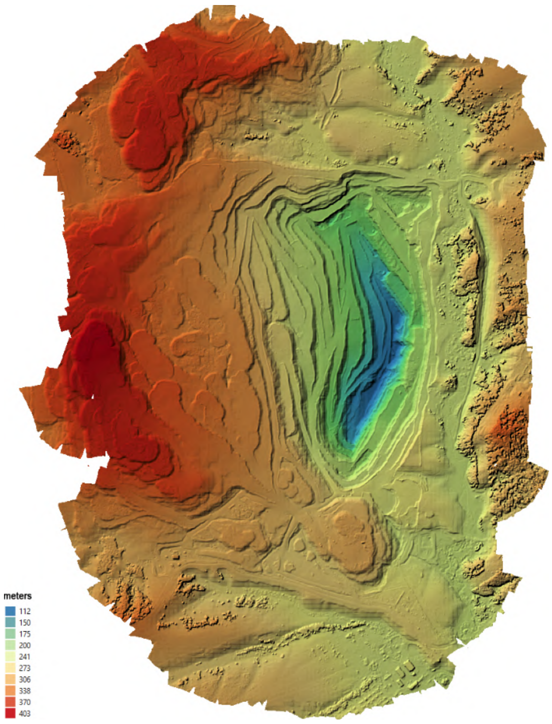

Figure 3: Digital terrain model of the “Vostochny” open pit.

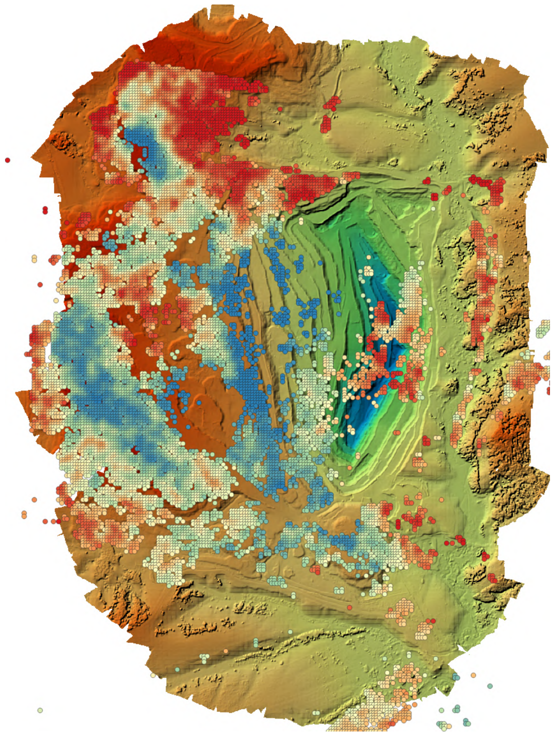

Figure 4: Digital terrain model of the “Vostochny” open pit with an overlaid map of average rates of change in vertical displacements.

part of the stockpile, where the rock extracted during mining is stored. In the western part of the stockpile, subsidence of the earth’s surface is recorded. Here, presumably, work is underway to level the stockpile, this is indirectly indicated by the rise of the earth’s surface on the sides. Drawdowns were also identified in the western part of the open pit on the border of the open pit and the stockpile. The mean displacement rates for the observation period ranged from -203 mm/year to $+117$ mm/year.

Thus, the use of radar data from the Sentinel-1 spacecraft is expedient for monitoring landslide phenomena, especially in areas with intensive mining operations. The results obtained can become the basis for the development of monitoring systems and measures to prevent landslides.

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