Earth Surface Subsidence in the Kuznetsk Coal Basin Caused by Manmade and Natural Seismic Activity According to ALOS PALSAR Interferometry

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***Abstract*—This paper presents results of a spaceborne radar interferometry technique application for land subsidence observations in a coal mining area in Kuzbass, Russia. Joint analysis of radar interferometry measurements with simultaneous seismic observations shows that the land subsidence is triggered by seismic events, both natural and caused by human underground activity. Surface displacements are linked typically to the boundaries of block structures and correlate with the location of clusters of seismic events.**

***Index Terms*—Coal mine, land surface subsidence, seismic measurements, spaceborne radar interferometry.**

I. Introduction

RADAR interferometry is a technique widely used to measure topography and surface small-scale displacements during the time interval between consecutive radar observations. The technique is based on the information about phase difference of the echo signals recorded by single-antenna SAR system in the repeated orbits (passes) observations of area of interest. The subtraction of digital elevation model phase in the differential radar interferometry (DInSAR) scheme allows the revelation of variations of the signal path length between the observations, including displacements of scattering surface. DInSAR technique provides a detailed map of the radial displacements of scattering surface elements with respect to radar in contrast with individual profiles or point measurements typically provided in field measurements. The small-scale surface displacements may be of different nature, including consequences of earthquakes, tectonic events, landslides, karst processes, or human activities. An object of our interest is surface subsidence in coal mining areas. Observation of such a type of soil subsidence by means of the DInSAR technique was described, for example, in [1]–[3]. Our study differs from similar ones published earlier by availability of synchronous seismological observations made by the ground seismology network deployed in the study area. Thanks to this, we can link unambiguously the Earth surface subsidence in the Kuznetsk coal basin detected by the DInSAR technique with the location of zones of intensive seismic activity.

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II. Methods

The radar interferometry technique is a long and very detailed framework. There are many publications describing an idea of the technique in detail (see, for example [4]). As it is known, phase difference in the interferogram $\Delta\varphi = \varphi_1 - \varphi_2$ depends on the following components:

$$\Delta\varphi = \Delta\varphi_t + \Delta\varphi_a + \Delta\varphi_d + \Delta\varphi_n + \Delta\varphi_0. \tag{1}$$

First of all, there is topographic phase difference, which is tied to topography height variations Δh as

$$\Delta\varphi_t = -\frac{4\pi l_p \Delta h}{\lambda r \tan\alpha} \tag{2}$$

where $-\lambda$ is the signal wavelength, r is the slant range from radar till surface point, α is the radar wave incidence angle, and l_p is the perpendicular component of interferometer spatial baseline. From (2), we can derive such important characteristics as height ambiguity interval h_a on the interferogram. If we accept $\Delta\varphi_t$ to be equal to 2π (2), we obtain

$$h_a = \frac{\lambda r}{2l_p}\tan\alpha. \tag{3}$$

Adjacent interferometric fringes on the interferogram with 2π phase difference correspond to surface elements with h_a difference in altitude. Typically, a height ambiguity interval h_a equals tens to hundreds of meters.

Component $\Delta\varphi_a$ describes variations of radar signal path length in the atmosphere. Atmospheric component $\Delta\varphi_a$ is a severe corrupting factor in interferometry. There are various techniques allowing the correction of atmospheric component, but the easiest one is to work with radar data corrupted by atmospheric irregularities to a less extent. For example, ttroposphere inhomogeneities in the case of heavy clouds may introduce two-way path-length variations up to 4 cm for the radar signal, but are typically small (less then 1 cm) under clear-skies weather conditions. The presence or absence of significant interfering ionospheric irregularities and respective phase shift on the interferograms can also be predicted using various indices of ionospheric disturbances.

Component of interest $\Delta\varphi_d$ characterizes displacement of the reflecting surface in radial direction, along the slant range line. Extraction of component $\Delta\varphi_d$, which describes dynamics of the underlying surface during time interval between radar observations, is the task of differential radar interferometry. Phase difference $\Delta\varphi_d$ is tied to the variation of slant ranges differences Δr_d caused by surface displacements by the following relationship:

$$\Delta\varphi_d = -\frac{4\pi}{\lambda}\Delta r_d. \tag{4}$$

Radar measures projection of vertical or horizontal surface displacements onto slant range line. For example, in the case of vertical displacement, Δz_d acts as surface subsidence or uplift as

$$\Delta\varphi_d = -\frac{4\pi}{\lambda}\Delta z_d \cos\alpha. \tag{5}$$

Component $\Delta\varphi_n$ characterizes noise of various nature on the interferogram. It includes receiver thermal noise as well as spatial and temporal decorrelation noise. The component cannot be estimated and removed accurately.

The component $\Delta\varphi_0$, which is an unknown systematic bias in the surface dynamics studies, may be estimated using a signal of stable surfaces and compensated later on. We will restrict ourselves to the regular interferometric processing in a given study; we will select and analyze radar signals with a fairly low degree of decorrelation (signals with high coherence). Therefore, we will not consider permanent scatterers interferometry technique [5]–[11], which assumes simultaneous processing of large image stacks.

III. Input Data

The test site is located in the Kuznetsk Basin—the area of strong human impact onto the Earth's crust. Active economic activity in the form of pit and underground coal mining affects the stress state of rocks, causing earthquakes. However, this area has also been seismically active long before the start of coal mining. In order to assess the feasibility of satellite DInSAR technique in our study and to map geodynamic processes in the form of surface subsidence—both natural and tied to seismic activity, which accompanies the coal development processes—we have chosen a test site with coal mines in the vicinity of Polysayevo city, Kemerovo region.

To detect the effects of seismic activity in the form of underlying surface deformation, we made an attempt to use radar data obtained in various frequency bands; however, due to a significant temporal decorrelation at higher frequencies, we have chosen finally lower frequency band, the L-band. All of the results presented in this paper were obtained using PALSAR

TABLE I
Interferometric Observations Geometry

Pair number	Observation dates: year, month, day	Height ambiguity h_a,	Perpendicular baseline component l_p, m h_a, m
1	20070122-20090127	106	-533
2	20070609-20070725	-140	410
3	20070725-20070909	-187	253
4	20071210-20080125	-96	450
5	20080628-20090816	-244	230
6	20080727-20090914	-33720	2
7	20100617-20100802	-218	277

L-band data (wavelength $\lambda = 24$ cm) from ALOS satellite (Japanese Aerospace Agency JAXA). Among the available data types, we selected those obtained in the highest surface resolution mode. These are the data obtained in FBS (observation mode with HH polarization combination) and FBD (observation mode with two combinations of polarizations—HH and HV) modes. FBS data are characterized by high spatial resolution on the surface (about 7 m), which provides the most detailed map of displacements. In FBD mode, the range resolution is twice lower. The peculiarity of interferometric observations in repeated orbits scheme using PALSAR data is that the shortest time interval between two consecutive observations is 46 days (exact orbit repetition period).

IV. Interferometric Technique and Results Obtained

For our study area, we selected and processed the next interferometric pairs (year, month, day): 20070122–20090127, 20070609–20070725, 20070725–20070909, 20071210–20080125, 20080628–20090816, 20080727–0090914, and 20100617–20100802.

Geometry parameters of the interferometric observations and meteorological conditions data during observation days are presented in Tables I and II. Sign of height ambiguity h_a, calculated according to (3), characterizes the sign of the phase change with rise of altitude. In the case of negative values, the phase increases with increase of altitude. To remove topography on the differential interferogram, we used SRTM DEM with 90-m surface resolution. As study area is characterized by intense economic activity, we may use the h_a in the analysis of interferograms to estimate the height of possible details of the relief created by man and to make correct conclusion about the nature of the observed variations of the phase difference on the interferogram.

We began our analysis with processing the interferometric pairs having long temporal baselines (time intervals between repeated observations) of more than one year. It was found that one year time interval is too large for this area. Two main effects—high temporal decorrelation and relatively quick displacements with high amplitude in various, sometimes overlapping, places preclude reliable interpretation of interferometric measurements.

The best results were obtained with interferometric pairs, collected with a shortest possible repeat period, which is equal to

TABLE II
METEOROLOGICAL CONDITIONS DURING OBSERVATIONS

Temperature, deg	Cloudness	Precipitations
-10/-20	no/ cumulus	no/light snow
9/17	cumulus translucent/ cumulostratus	no/no
17/10	cumulostratus /cumulus translucent	no/no
-17/-18	no/ no	no/no
20/13	cumulo-nimbus/ cumulus translucent	no/no
20/9	no/ cumulus translucent	no/no
12/ 11	no/ no	no/ no

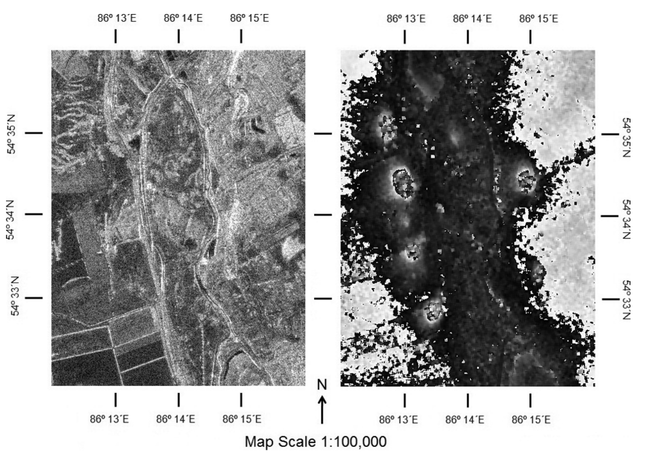

Fig. 1. (a) Amplitude image and (b) interferogram for interferometric pair June 17 and August 2, 2010.

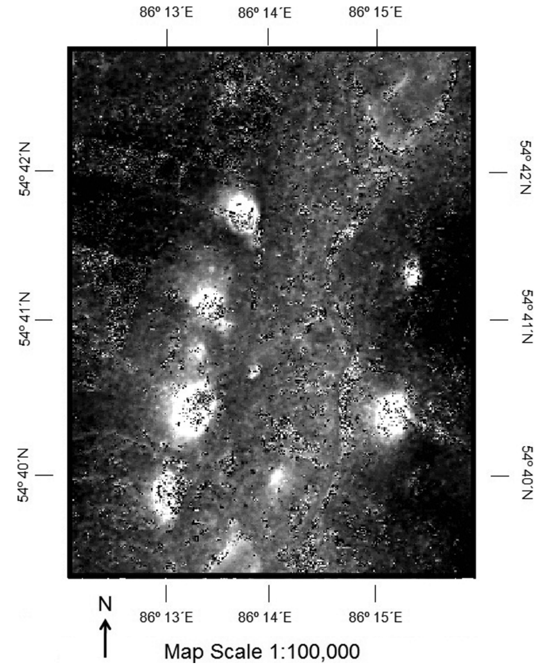

Fig. 2. Unwrapped interferogram in grayscale colors for interferometric pair June 17 and August 2, 2010.

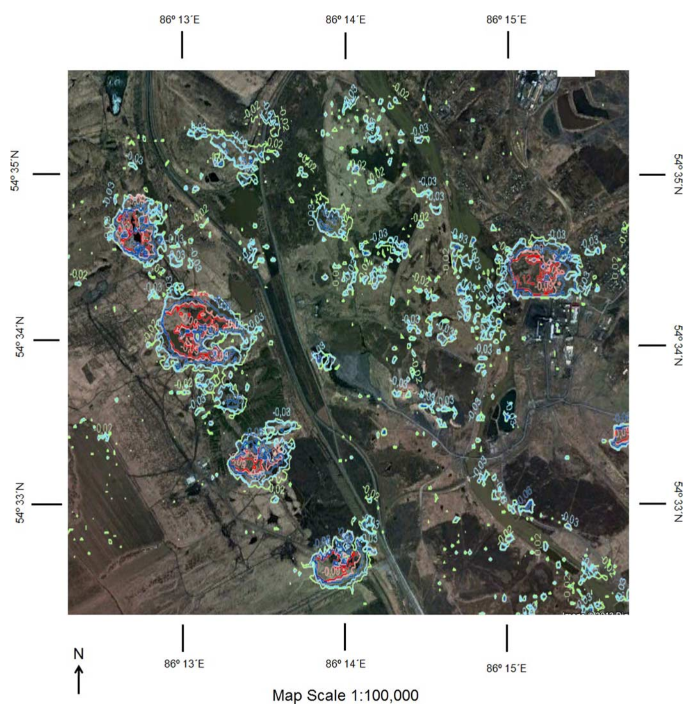

Fig. 3. Google browse image with soil subsidence contours overlaid for interferometric pair June 17 and August 2, 2010.

46 days for PALSAR. Analysis of the interferogram in Fig. 1 (observations on June 17 and August 2, 2010) shows that it is very likely that fairly strong dynamics of the surface occurs in this region. An entire brightness cycle on interferogram corresponds to the radial displacement of the surface at the distance of half signal wavelength, which is about 12 cm.

On the fragment of unwrapped interferogram (Fig. 2), bright spots (according to the grayscale palette used) correspond to the earth's surface subsidence in the summer of 2010 during 46 days of PALSAR repeat orbit interval. The same results are represented in Fig. 3 in a form of contours of equal displacements overlaid onto a georeferenced image from the Google web portal. Values of the vertical surface subsidence Δz_d here were calculated using (5). Green contours mark isolines of 2-cm subsidence, blue ones correspond to 3 cm, dark blue to -6 cm, pink to -9 cm, and red to -12 cm. The largest subsidence of 13 cm was observed in the areas outside of this figure.

Archival PALSAR SAR data provide us the chance to observe Earth surface dynamics in this area in other years. In Fig. 4, there is a series of interferograms fragments obtained with a repetition period of 46 days in 2007 and 2010.

Elliptical patterns with 300–500 linear sizes may be seen on all of these fragments. Interferometric phase increases approximately at 2 π from the edge of patterns to the center. If we interpret these patterns as topography features not presented on SRTM DEM we used to correct for the topography, then, according to h_a from Table I, heights of these elevations

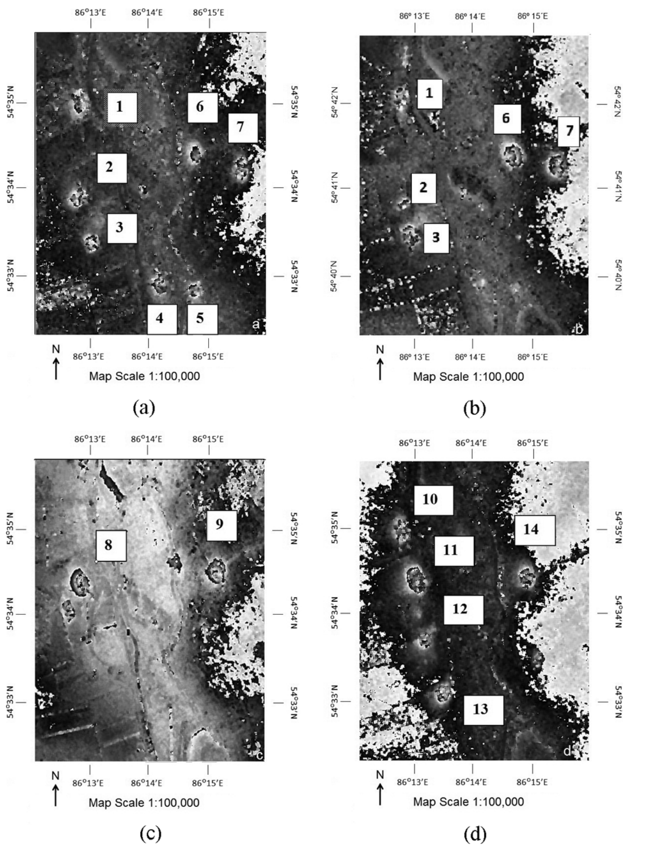

Fig. 4. Stack of interferograms obtained in 2007 and 2010. (a) 20070609–20070725. (b) 20070725–20070909. (c) 20071210–20080125. (d) 20100617–20100802.

produced because of human activity should exceed 100–200 m, which is incredible. These details cannot be generated also by atmospheric inhomogeneities, which usually have different morphology on the interferogram and introduce few times smaller phase shift. Cumulonimbus clouds, for example, are usually most clearly apparent on the interferogram; they generate 2–4-cm deviations of the signal path length in the form of furrows [12]. In all other cases, including ours, the fluctuations of the path length should be much smaller. Possible fluctuations of the total electron content in the ionosphere also cannot provide such details on the interferogram because typical distortions due to ionospheric irregularities have the form of narrow elongated strips tens of miles long on the interferogram and lie almost parallel to the slant range direction [13]. Some of the observed features are concentrated in the vicinity of underground coal mining in Polysaevo. They appear on some interefrograms and disappear on others. Phase increments from feature edge to the center may indicate surface subsidence at half wavelength distance, or at 12 cm in the linear scale, or even more.

Comparing interferograms in Fig. 4(a) and (b), which were obtained in the summer of 2007, we may note that most of the features are present on both images, although the intensity of subsidence is different. In Fig. 4(b), features 1–3 become less apparent, and features 4–5 almost disappeared. Features 6–7, on the contrary, become stronger and closer to each other.

In Fig. 4(c), in December 2007, which was five months later, there are only two features visible—numbers 8 and 9. Feature 8 is shifted upward with respect to feature 2 from interferograms mentioned before; faint traces of the latter one are almost unseen. Feature 9 is located between features 6 and 7 from Fig. 4(b).

On the interferogram from Fig. 4(d), dated 2010, there are many new features compared with Fig. 4(c). The location of feature 10 coincides with the location of feature 1 from the interferogram from the summer of 2007. Features 12 and 13 are new ones, and features 11 and 14 remind us of features 8 and 9 seen in Fig. 4(c), but they become closer to each other. In general, spatial distribution of features in 2010 is much different compared with those in 2007.

V. Interpretation of the Data in Combination With Terrestrial Seismology Observations

The nature of the observed dynamics may be revealed thanks to the availability of simultaneous terrestrial seismological observations, made by ground-based seismic stations network in mid 2007 to the beginning of 2008 [14]. Processing of the data collected by network of sensors allowed mapping the location of the earthquakes epicenters and estimation of their depths. It is known that the extraction of coal by underground or open pit method strongly affects the stress state of rocks and provokes earthquakes. Experiments on monitoring the seismic activity by means of seismic stations network in the Polysayevo area were conducted in three phases, of which we are interested mostly in the time intervals from August 13 to September 11, 2007, and November 1, 2007, to January 31, 2008.

Seismic tomography information revealed block structure of sediments in the area of seismic activity. It was discovered that subsidences identified by means of SAR interferometry, both manmade and natural ones, are linked to boundaries of blocks with different seismic waves velocities [14].

We have to mention that the chain of features on the left side of interferograms is not tied to mines. Those are natural activizations. Seismic events occur fairly regularly here, with 2–3 km depth of earthquake epicenter. The frequency of events is from a few to several dozens per day. A characteristic feature of these activations is that their energy class is one to two grades higher compared with the average.

Fig. 5 shows a map of the epicenters of the events recorded during the first time interval. Two clusters of epicenters seen here correspond to two lavas with active coal mining—Breevsky and Tolmachevsky mines. In Fig. 4(b), they correspond to features 6 and 7, respectively. Other details are almost unseen; they did not appear on the map of earthquake epicenters. Later on, in early 2008, these clusters of seismic events migrated in the space along with the coalface. The second period of observation is interesting because of the fact that all activities in the Breevskoy mines stopped in January 2008. According to seismology data, the intensity of seismic events in its place decreased from 20 to 30 events per day in November up to one to two events per day in January. Feature 6 in Fig. 4(b), corresponding to the location of coalface, has practically vanished in Fig. 4(c). A small spot to the left of feature 9 in this figure indicates the location of the coalface.

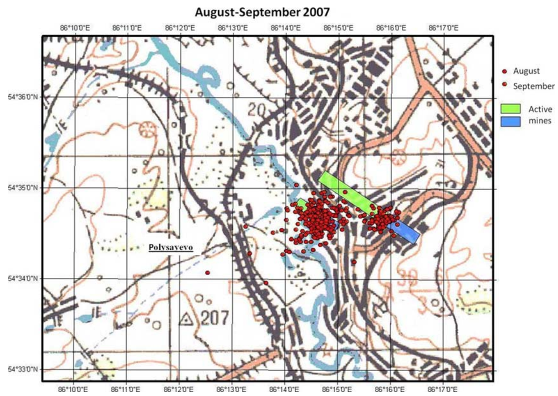

Fig. 5. Location of earthquake epicenters during time interval August–September 2007 according to seismological network data.

Feature 9 in Fig. 4(c) is a region with active excavations in the Tolmachevsky mine: it moved from the location of part 7 in Fig. 4(b) to the left. In Fig. 4(d), this feature coincides with feature 14. The depth of the seismic events epicenters in these mines is about approximately 700–900 m, while the depth of coalfaces is just about 400 m. The most probable mechanism for the events here is uplift-like one. The fact that seismic events are located deeply under the areas of coal mining allows us to suggest that, in the case of highly stressed state of rocks, even slightly varying properties of the medium during mines development may trigger seismic activations.

VI. Conclusion

Earth surface subsidence in the Kuznetsk Basin, near Polysayevo city, was detected by means of satellite radar interferometry. Displacements are usually short-term events and are caused by seismic activity both natural and manmade nature. Linear size of subsiding surface spots is about 300–500 m. Amplitude of the vertical displacements is of the order of 12–15 cm. According to seismological observations made by network of seismic stations, the location of displacements is linked usually to the boundaries of block structures and correlates with the location of clusters of seismic events. The results obtained in our study provide a scientific basis for establishment of mining operational monitoring systems in areas of intense subsidence because of extensive underground excavation activities

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