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URBAN AREA GEODYNAMIC RISK MAPPING USING LONG-TERM TIME SERIES OF SENTINEL-1 SATELLITE RADAR INTERFEROMETRY

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Abstract: Kryvyi Rih is a city in the Dnipropetrovsk region of the South-eastern part of Ukraine, the main steel industry city of Eastern Europe and a globally important center of the iron ore mining and metallurgy. The area includes technogenically affected land under geodynamic disasters risk. This article describes the use of satellite radar interferometry time series analysis and geological/geophysical data to map geodynamic risk of the Kryvyi Rih city's central part. Long-term time series of Sentinel-1 satellite differential InSAR measurements were engaged for this purpose. Detecting and mapping the high-precision land surface movement dynamics serves as an important indicator of potential environmental vulnerability. The article presents the technique used for analysis of the time series of small displacements of the land surface and their interpretation. Geological and geophysical data are auxiliary for risk forecasting and the production of geodynamic risk maps of the study area.

Keywords: Geodynamic risk mapping, synthetic aperture radar, satellite radar interferometry, time series analysis, Kryvyi Rih.

Abbreviations used

ESA	European Space Agency
InSAR	Interferometric Synthetic Aperture Radar
IW	Interferometric Wide
IW SLC	Interferometric Wide swath mode for Sentinel-1 satellite, primary conflict-free mode over land, spatial resolution (single look) of 250 km swath at 5 m by 20 m
SAR	Synthetic Aperture Radar

TOPSAR Terrain Observation with Progressive Scans SAR, when the beam is electronically steered from backward to forward in the azimuth direction for each burst, avoiding scalloping and resulting in homogeneous image quality throughout the swath. TOPSAR mode replaces the conventional ScanSAR mode, achieving the same coverage and resolution as ScanSAR, but with a nearly uniform signal-to-noise ratio and distributed target ambiguity ratio.

Introduction

The city of Kryvyi Rih is a unique place in the world from many points of view, but referring to the topic of this paper – mainly from the point of unprecedented damage to the geological environment within residential areas. It is due to both: the mining and processing of iron ores on the one hand, and on the other hand – due to the waste storages from related industries through all over the territory of the city (more, than 140 km long). Due to the extraction of billions of tons of rock from the earth's interior, underground cavities, zones of mass deformations, rock displacements, natural and man-made faults, etc., were formed in the rock massif.

The Kryvyi Rih iron ores were discovered on the Ingulets’ river banks in 1781. The first mining there was opened in 1875. During 1939-1958 the systematic geological survey of this area was carried out by the team under the supervision of Y. Belevtsev. A series of maps was produced manually, which used to be the main source of information for many years for further phenomena research and the development of iron ore industry.[1] Since then those maps were not much updated. However, In this respect taking into account mentioned above and using additional geological and geophysical data, the authors consider newly developed methods of geodynamic risk evaluation and remote sensing for the purpose of detecting and mapping the high-precision land surface movement dynamics and so predicting the most vulnerable zones in the centre of the city.

Study area

From the geology point of view, the Kryvyi Rih iron ore basin represents the southern margin of the Kryvorizhskyi-Kremenchukskyi through of a large Proterozoic geosyncline composed of metamorphic rocks of the Kryvyi Rih series resting with structural unconformity on the eroded surface of the Archean rocks of the Dnieper block. The Kryvyi Rih synclinore is much affected by large tectonic faults, block uplifts, and subsidence. As a result, in many places it is represented by the second-order folds, which reflect the general synclinore pattern. Within the area of the Kryvyi Rih city, the synclinore is presented in its most complete form. It is expressed by a series of large folds complicated with a high-order folding and numerous fractures.[2]

Powerful industrial area around the city was formed as the result of the Kryvbas deposits development. Vigorous technogenic activity runs on for many years within the Kryvyi Rih urban area. Minerals are mined by open-pit method. More than 35 thousand hectares of land were disturbed due to mining processing. Powerful anthropogenic impact on the geological environment can be observed within the 585 km^2 area of Kryvyi Rih basin. This circumstance leads to changes in the regional landscape as well as in geological and hydrogeological conditions.[3]

The massifs of ancient rocks where the industrial and residential complexes located are now largely decompressioned sections of the upper earth crust. The zones of technogenic fracture are also available in the sedimentary cover (Figure 1). This contributes to a significant reduction of seismic stability of the area, increasing the probability of vertical and horizontal displacements of individual units.

The main reason is the excessive man-caused load on the blocks and the fracture zones due to the construction of dumps, tailings and reservoirs.[4] Separate dumps occupy the area of small blocks, and tailing pits are often located over the faults' zones.

Background

As we mentioned above, the study area has been under thorough conventional geological and geophysical investigation for more, than a hundred years. So, there is a recognized need in involvement and wider usage of new methods, partially, remote sensing data, that are of current interest.[5] These methods will contribute to a comprehensive solution to the problem of the geological environment destruction. In addition, it will enable to carry out a full analysis of space images of the Kryvyi Rih city regions and to develop a series of state-of-the-art maps of vulnerable to destruction zones.

Recently in the variety of tasks becomes wider uses the method of satellite differential radar interferometry,[6] which detects the small land surface displacements with high accuracy.

Data collection

In 2014, the ESA has launched the Sentinel mission. Sentinel-1 is the first of the five missions that the ESA is developing under the Copernicus initiative. Sentinel-1A was launched on 3 April 2014 and its twin Sentinel-1B on 25 April 2016. The Sentinel-1 mission comprises a constellation of two polar-orbiting satellites (flying attitude 693 km, inclination 98.18 degree), operating day and night performing C-band synthetic aperture radar imaging, enabling them to acquire imagery regardless of the weather. Sentinel-1 works in a pre-programmed operation mode to avoid conflicts and to produce a consistent long-term data archive built for applications based on long time series.

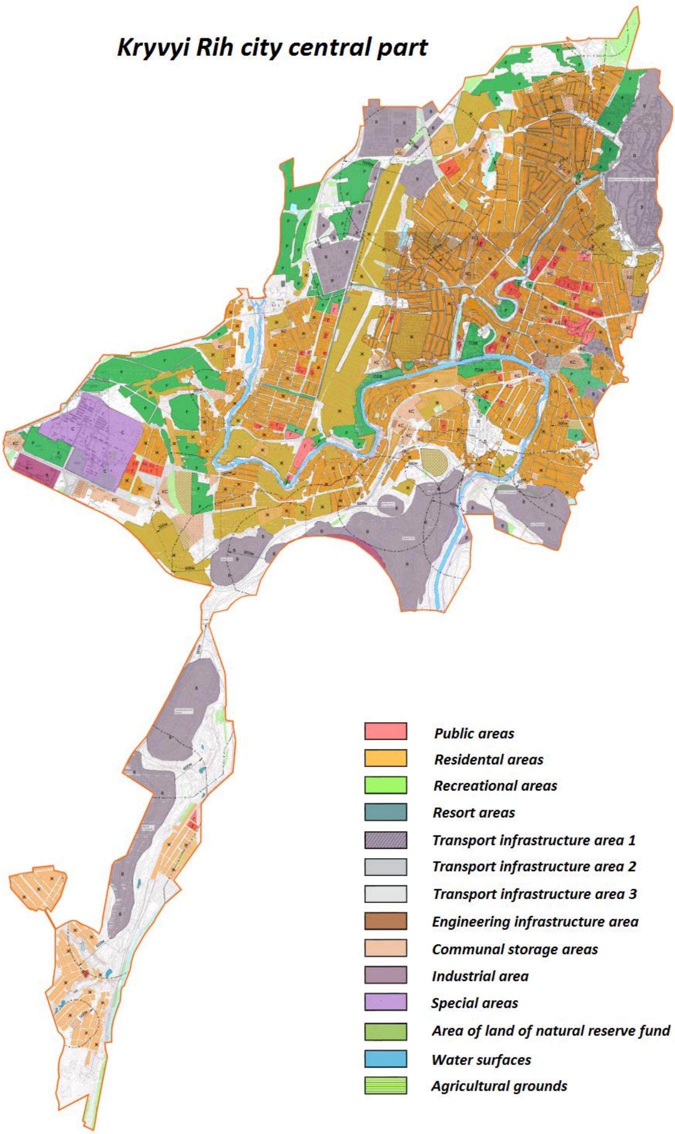


Figure 1: Study area functional zoning map.

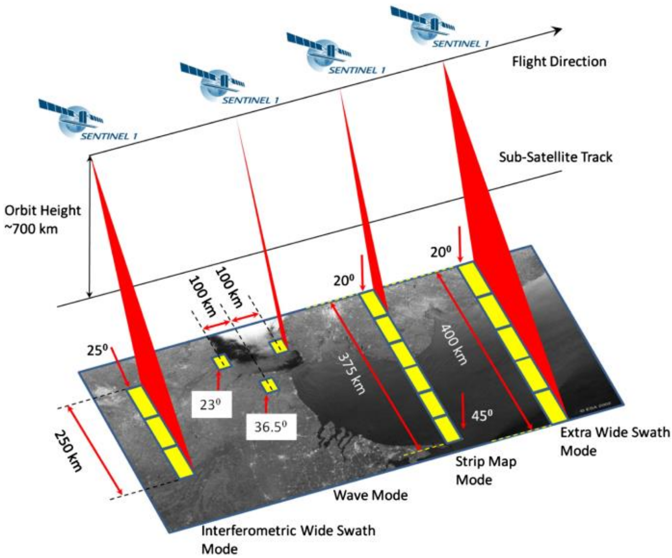


Figure 2: Imaging modes of Sentinel-1.

Mission Orbit	- Sun-synchronous, near-polar, circular orbit - 693 km orbit height - 98.18° inclination - 12 day repeat cycle at Equator with one satellite, 175 orbits/cycle
Satellite platform	- 3-axis stabilized, yaw/pitch/roll steering (zero Doppler) - 0.01° attitude accuracy (each axis) - Right looking flight attitude - 10 m orbit knowledge (each axis, 3σ) using GPS - Spacecraft availability: 0.998 - Solar array power: 5 900 W - Science data storage capability: 1 410 Gb - Communication links: X-band data downlink and optical data link through EDRS for payload data at 520 Mbit/s; S-band 64 kbps uplink and 128 kbps / 2 Mbps downlink for TM/TC

Instrument Payload	- C-band Synthetic Aperture Radar - Centre frequency: 5.405 GHz - Polarisation: VV+VH, HH+HV, HH, VV - Incidence angle: 20° - 45° - Radiometric accuracy: 1 dB (3σ) - NESZ: -22 dB, DTAR: -22 dB, PTAR: -25 dB
Modes, Swatch Widths and Resolution	- Strip Map Mode: 80 km swath, 5 x 5 m spatial resolution - Interferometric Wide Swath: 250 km swath, 5 x 20 m spatial resolution - Extra-Wide Swath Mode: 400 km swath, 20 x 40 m spatial resolution - Wave-Mode: 20 x 20 km, 5 x 5 m spatial resolution

The Sentinel-1A and Sentinel-1B twins satellites provide SAR data to Copernicus Services (http://www.copernicus.eu) with 5-6 days revisited time.[7]

In current study totally 66 Sentinel-1A/B radar images were acquired from Copernicus Open Access Hub (https://scihub.copernicus.eu/dhus/) for period from 7 July 2016 to 7 August 2017.

Processing

The methodology for interferometric processing is provided. For constructing an interferogram the Sentinel-1 interferometric SAR Single Look Complex (SLC) products must be taken in pairs with difference between images of 6-12 days to determine the changes in the land surface.

Sentinel Application Platform (SNAP) the open-source software provided by ESA was used for satellite radar interferometry data processing.[8]

Principal step in interferogram generation is co-registration. A pair of the images is composed into a joint stack in order to each ground target contributes to the same pixel in both images. Because of Interferometric Wide (IW) SLC Sentinel-1 images are generated by series of bursts. Further deburst operator from the Sentinel-1 toolbox menu applied for seamless integration of all burst data into a single image. After that, the interferogram is formed and flattened by removing the topographic phase. Filtering the phase increased proper implementation the signal-to-noise ratio. The Statistical-cost, Network-flow Algorithm for Phase Unwrapping (SNAPHU) applied to Sentinel-1 as well.[9]

Distances in SAR images are distorted because of topographical variations of a scene the tilt of the satellite sensor's sight axis. Terrain corrections compensated these distortions. The geometric representation of the image will be as close as possible to the real land surface. Terrain correction applied to the phase band enables geocoding the output product.

Time Series Analysis

As mentioned above, totally 33 Sentinel-1 interferometric pairs were formed. The same data processing technique are applied to each pair of SAR images individually for radar interferometry. The output of each pair of images processing is precision terrain elevations map (Figure 3).

So, the time series of 33 elevations maps was produced. The pixel-by-pixel simultaneous processing of all elevation maps resulted in spatial distributions of several important parameters of time series, which describe the linear trend, the periodic component and noise. Thus, the total number of time series parameters for further risk analysis is 6, its distribution maps are shown in Figure 4 (*a* – *f*).

Obtained maps in bulk describe the recent geodynamic conditions within study area and effectively complement the existing geological and geophysical data with present-day observations.

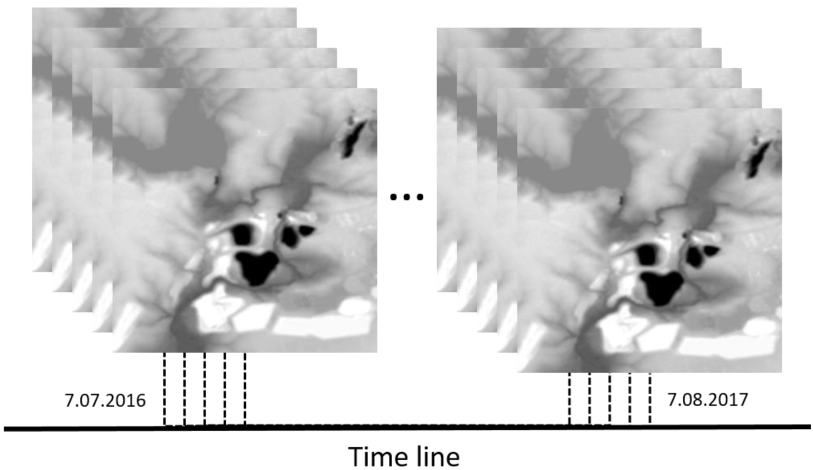
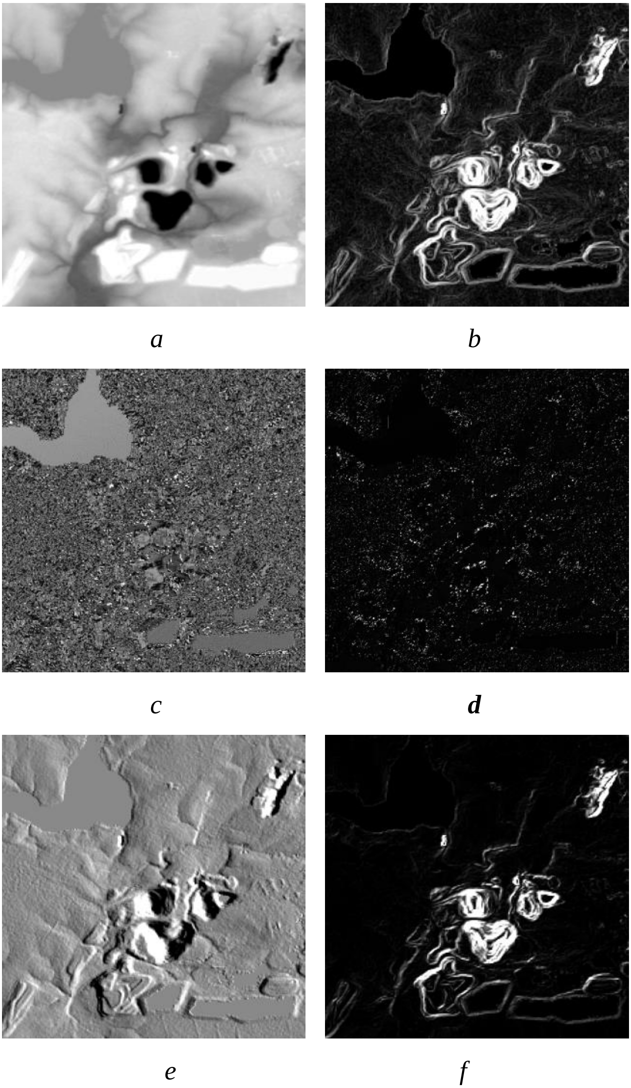


Figure 3: Terrain elevations maps time series from radar interferometry.



a - all-time average, m; *b* - standard deviation, m; *c* - periodic likelihood ratio,
d - most significant period, days; *e* - monthly rate, m;
f - resonance harmonic amplitude, m

Figure 4: Maps of radar interferometry time series parameters.

Results

In general, vulnerable sites at the researched area are arranged sporadically and the total amplitudes of the vertical earth's crust movements during the Quaternary period are of relatively low intensity. In some cases (the upper right corner of the image, Figure 3) it coincides with multistoried residential area and communication infrastructure and in this respect may be worth more attention.

Also, long-term time series of radar satellite imagery, which should be more than a few years at least, are important for determining these indicators. As a result of geodynamic risk mapping of highly urbanized area, we can confirm that the technique presented is worth implementing tool for analysis of geological potential vulnerability to hazard.

Data analysis

In our opinion, the interpretation of the terrain elevation dynamics concerning the possible development of subsidence and rock holes in the Kryvyi Rih city central part should be considered in close unity with the neotectonics of the study area. The investigated territory is located on the border of the large Western-Ingulets uplift and Serednyoprydniprovskyi megablock, in the zone of the powerful active Kryvyi Rih-Kremenchuk deep fault with the right shift kinematics.[10]

This geotectonic position predetermines the active development of neotectonic movements, both horizontally and vertically.[11] According to high-precision leveling data, the speeds of modern horizontal and vertical tectonic movements are estimated as of 2-10 mm per year.[12]

Two the most informative data layers – all-time average and monthly rate – were selected for the analysis and geological interpretation of the Sentinel-1A radar time series. The rest of estimates were not very informative outside the actively operating quarries and dumps.

The obtained average values of terrain elevation for more than half a year period almost accurately reflect the hypsometry of the preset-day relief. This conclusion is confirmed by the coincidence of the hypsometric level contours obtained as a result of the ASTER GDEM (https://asterweb.jpl.nasa.gov/gdem.asp) data processing. At the same time, a systematic difference in elevation of about 10 m has been detected (both for negative and positive values). Obviously, the proposed approach makes it possible to significantly improve the accuracy of hypsometric constructions with the help of remote sensing. Let us note that it is necessary to introduce empirical corrections for a certain values generalization so to get the reliable relief plastics.

The most informative, in our opinion, turned to be the map of the monthly rate in the hypsometry values of the researched area day surface. Along with the stable rates (both positive and negative) which are typical for territories with actively operated mine workings and dumps, local sections of monthly negative values are recorded within the residential section. The areas located outside the valleys of a developed hydro system are of high interest. However, sites in the north-eastern part of the region, where subsidence from 1 to 2 cm per month is fixed, deserve particular attention as they are located on the same line with the zone of the Kryvyi Rih-Kremenchuk deep fault. Along this zone, to the northeast, an extended strip of mass rock holes is observed. As a rule, they are associated with abandoned and operating mine workings. At the same time, in our view, discharge of the rocks tectonic stresses along the active faults zone can serve as the trigger mechanism for the formation of holes (falls). Alternation of linear sections of the northeasterly strike with positive and negative values of monthly rates may well indicate the current activity of this zone.

The development of linear sections of positive growth values (from 2 to 3 cm per months) of the northwest strike can be understand as an indicator of the development of compression and vertical uplift zones that were provoked by shear stress along the Kryvyi Rih-Kremenchuk deep fault zone.

So, the data obtained make it possible to estimate the neotectonic movements' dynamics for a particular territory and to identify potentially hazardous areas of possible subsidence and holes development over the mine workings.

Conclusion

In summarize, the technique described is a useful and versatile tool for analysis of geological emergency hazard. In the future after additional testing and along with conventional methods, it can be effectively used for assessing the geological emergency risk for a relatively low cost. Moreover, it will definitely enable to develop a series of state-of-the-art maps of vulnerable to destruction areas. The satellite radar interferometry integration with ground-based geological and geophysical data is especially useful. Geospatial analysis of satellite and ground observations and instrumental measurements allows to obtain new information about land surface neotectonic movements and geophysical fields anomalies within the Kryvbas territory. The outputs of research will be very important for geodynamic risks minimization and the safe natural resources management in the city of Krivyy Rih.

Future works should be aimed to improving the interferometric mapping accuracy by implementing a ground-truth geodetic points' network within the study area, as well as by integrating with local geophysical data.

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