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Continuous long-term (2016-2021) monitoring of the surface deformations in the Upper Silesian Coal Basin, Poland

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ABSTRACT

The Upper Silesian Coal Basin (USCB), located in Southern Poland, is one of the biggest coal deposits in Europe. It is continuously exploited since 18 century and it is one of the main industrial factors in the regional economy. As a result this is also the second populated region in Poland with 4.5 million inhabitants in the administrative province of Silesia. The extensive extractions of the underground coal resources in USCB trigger significant terrain changes leading to subsidence exceeding 1.5 m per year in some areas. Within the frames of two consecutive phases of the Polish contribution to the European Plate Observing System (EPOS) initiative, namely EPOS-PL and EPOS-PL+, a long-term monitoring over the area of USCB is performed using the advantages of the Differential Synthetic Aperture Radar (DInSAR) technology. C-band radar images acquired by the European Space Agency's Sentinel-1 mission comprising the period between the years of 2016 and 2021 are processed to delineate the range and amplitude of the deformation zones for chosen test sites. The Sentinel-1 constellation provides imagery with revisit time of 6 days, higher than the classical techniques. The standard approach include measurements like levelling, performed 2 to 6 times per year over chosen lines, or measurements with Global Navigation Satellite System (GNSS), while the DInSAR approach gives wider in space and time coverage. The long period of observations gives the opportunity to assess the surface behavior due to the coal underground extractions and to construct more precisely the model of deformations.

I. INTRODUCTION

The concept for an European infrastructure for integrating and distributing scientific digital data for multidisciplinary solid Earth science rose in the beginning of 21st century. In 2010 the European Commission funded the first preparation stage for developing the European Plate Observing System (EPOS; https://www.epos-eu.org/). The goal is to create an integrated space for data and services gathered by institutions and scientists from all around Europe, aiming to support the global monitor and study of the solid Earth system. In the following years different European structures initiated the development of regional infrastructures, that later would contribute to the Integrated Core Services (ICS) that will ensure the interoperability of the data and services gathered in the EPOS' so-called Thematic Core Services (TCS).

In 2016, the first phase of the Polish realization of EPOS began with the start of the EPOS-PL project (https://epos-pl.eu/). The structure of the project defined several Research Infrastructure Centers (RIC) on state level to provide datasets and services in given research fields, like gravimetry, seismicity, geodesy, etc. As a second level of the EPOS-PL development the first Polish EPOS infrastructures were created in two polygons were measurements from different observations for monitoring geodynamic processes was integrated. Two polygons from the group of MUSE – Multidisciplinary Upper Silesian Episode, were established in the area of intensive underground coal mining in the Upper Silesian Coal Basin (USCB) in Southern Poland. In the area of MUSE1 and MUSE2 (Figure 1) an in-situ integrated geodetic observation system was built, comprising GNSS permanent stations, campaign GNSS and levelling measurements, also artificial corner reflectors used for calibration of satellite radar measurements. The polygons include also geophysical observation system from seismological, gravimetric and geophysical networks. The collected data are shared as USCB episode in the TCS Anthropogenic hazard platform (https://tcs.ah-epos.eu).

Within EPOS-PL project the surface deformations caused by the coal extraction in USCB were, in addition to all other techniques, monitored with the application of the Differential Interferometric Synthetic Aperture Radar (DInSAR) technique. The method is chosen due to the possibility of automation of the processing for delivering of services for regular monitoring of the mine-induced deformations. The character of this deformations is determined by relatively shallow works

– between 400 and 1000 m, with high intensity and considerable volume of extracted underground materials. As a consequence, the observed area suffers from very dynamic ground changes in vertical but also in horizontal directions. The latter is a result of the used mining technique, namely long-wall mining, in which the resources are extracted in multiple layers, panel by panel, usually in 1 or 3-month intervals. The resulted surface deformations has a pattern of multiple distributed smaller patches with non-liner horizontal and vertical development. The horizontal position of the appearing deformation spots follows with several months (6-8 months) the time of the extraction due to the cavity compaction (Ilieva *et al.*, 2019). In the first phase of the Polish EPOS project, namely EPOS-PL, we developed the first concept for an improved DInSAR post-processing (Ilieva *et al.*, 2019) aiming to reduce the effects of the atmosphere artifacts and unwrapping errors. Our tests were made for the area of Bytom mine (Figure 1) where the annual subsidence is estimated in the range around 1.50 m.

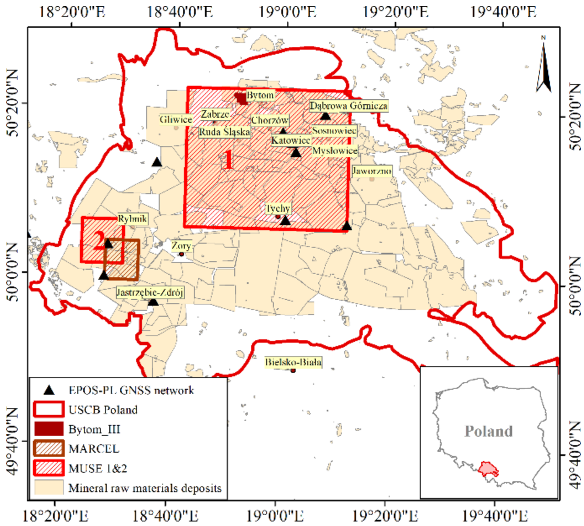


Figure 1. Upper Silesian Coal Basin (USCB) in Southern Poland with the test sites MUSE 1&2 (EPOS-PL) and MARCEL (EPOS-PL+), EPOS-PL permanent GNSS network, and the coverage of the mining deposits.

In the next phase of the study, the second part of the Polish realization of EPOS started in 2020 as EPOS-PL+ project (https://epos-pl-plus.eu/). Thanks to the significance of the results for MUSE episodes, an InSAR dedicated center was created - Satellite Data Research Infrastructure Center (CIBDS). In CIBDS we are developing an improved algorithm for post-processing, that will allow robust automation of the DInSAR work-flow. The goal is to create a stable service of regular deformation maps that at the next part of the project will also allow the development of prediction models of the expected surface deformations. Such a service will enhance monitoring and decision-making process in the mining industry. We expanded our researches over the test site of MARCEL mine (Figure 1) in USCB, where we also monitor the stability of two safely pillars. To validate our DInSAR solution we established dense in-situ network in the area of the pillars and the surroundings where we already performed two campaigns of levelling and GNSS measurements.

II. IMPROVED DINSAR POST-PROCESSING APPROACH

The Differential Interferometric Synthetic Aperture Radar (DInSAR) is considered as the classical satellite radar approach for monitoring of Earth's surface deformations caused by natural or anthropogenic hazards. Since the first notable results acquired with this technique in the 90 s of the 20th century (*e.g.* Massonnet *et al.*, 1993) DInSAR method was developed further with several advanced InSAR techniques like Persistent Scattered Interferometry (PSInSAR; Ferretti *et al.*, 2000) and Small Baseline Subsets (SBAS; Berardino *et al.*, 2002). These techniques have the advantage of minimizing the atmospheric errors on the radar signals by creation of a stacks of SAR images, based on the pixels with highest quality in time (highest coherence). On the other hand, they are not capable to keep information in the areas with fast dynamics or with non-linear movement, like in the coal fields of USCB. This is the reason why in CIBDS we also use the classical DInSAR monitoring. In this method we apply consecutive DInSAR, in which for every next interferometric pair (*e.g.* interferogram *j* in Figure 2) the first SAR image (the primary or master *j* image) is the second (or slave *i* image) of the previous pair – interferogram *i*. In this way we preserve continues time series of differential interferograms. On one hand, this approach has the capability to cancel out the atmospheric influence in one image that would appear with opposite signs in the two common consecutive interferograms. On the other hand, if a longer period of atmospheric perturbance exists in the timeline, it could affect the entire series. Still, despite this disadvantage, the method is valuable with gathering information about the range of subsidence in the center of the subsidence bowls. To estimate the total subsidence in the area of interest we combine the consecutive deformation maps in cumulative solution.

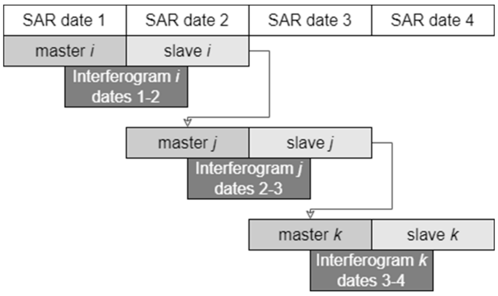


Figure 2. Consecutive DInSAR.

In order to minimize the influences from unstable atmospheric conditions, unwrapping jumps, but also residual orbital ramp and reference uncertainties in the separated interferograms, we propose an improved method for post-processing firstly suggested in EPOS-PL

(Ilieva *et al.*, 2019) and currently under improvement in EPOS-PL+. The method is based on the removal of a oscillating surface from each interferogram (Figure 3), aiming to anchor the entire series of deformation maps to a surface build on common, stable in time, highly coherent points (>0.9).

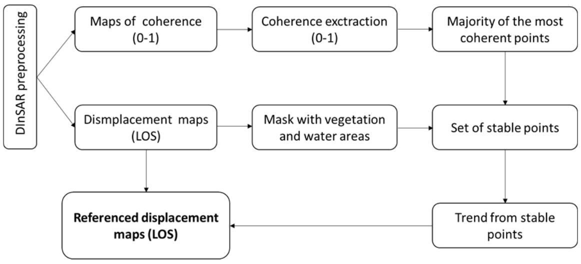


Figure 3. Scheme of the proposed post-processing approach for georeferencing to a surface with common origin.

We extract the most coherent pixels of each interferogram and find which of them keep this quality throughout the entire year. These pixels have a majority for a set of about 60 interferograms in the case of SAR data acquired at 6-days interval that we used – data generated by the SAR sensors mounted on the constellation of two Sentinel-1 (A&B) European Space Agency's (ESA) satellites. This group of points represents the pixels with good reflectivity throughout the entire year, covering all seasonal changes. We also exclude the areas of known deformations. Than we use this set of points to extract the values from displacement maps and based on the latter to construct an interpolated surface that represents to fluctuations from the zero origin. This trend is removed from the corresponding displacement map leading to unification of the datum for the entire set of deformation maps.

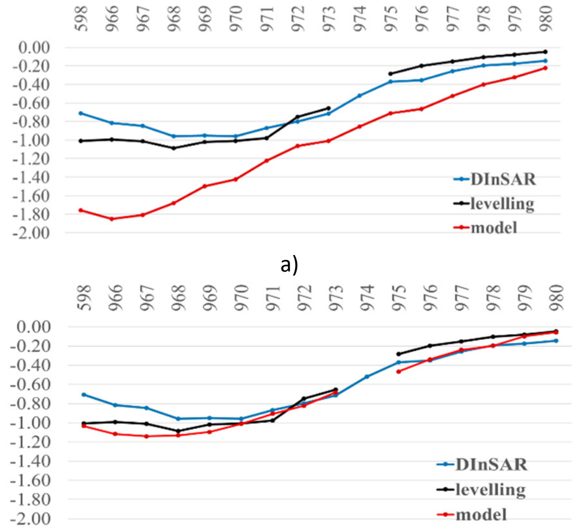
At the next step, the automation of the process continues with processing of a new interferogram every time when a new Sentinel-1 image is released by ESA, but not before the corrected orbit file is also available. In this approach it is not necessary to re-processes the entire stack as in the case of some other advanced InSAR methods. The only update is in the check of the stability of the coherence points from the new interferogram in the period of one year prior the last Sentinel-1 acquisition.

As it was mentioned earlier the quality of some deformation maps suffers from the atmospheric perturbance influence. In separate cases this effect is too strong and cannot be eliminated. When it affect short period of time (up to 12 days, or 1 interferogram with low quality) we apply linear interpolation to fill the gap of excluded data, while for minimizing the effect of longer periods of data with lower quality we will integrate machine learning, including Neural Network (NN) approaches. To evaluate the quality and to point out the outliers we do an assessment based on the statistical characteristics of the deformation maps, namely by application of Z-score method for the mean and standard deviation values of each image. The goal is to improve the smoothness, meaning to minimize the unexpected jumps in the time series generated in the DInSAR deformation maps.

III. SUBSIDENCE PREDICTION

A. *Knothe-Budryk theory modelling*

In the first EPOS-PL project a collaboration between the two teams from the Institute of Geodesy and Geoinformatics in Wrocław University of Environmental and Life Sciences – responsible for DInSAR processing, and the Department of Surface and Structures Protection, Central Mining Institute who is responsible for subsidence modelling and prediction, started. The standard approach for prediction of mining-induced surface deformation in Poland is to use regular levelling measurements preformed along monitoring lines or set of points in 1 to 6 months intervals as main input data in the Knothe-Budryk method (Knothe, 1953, Kowalski, 2015). We started with comparison of these modelled deformation with a one-year (2017) collection of DInSAR deformation maps over a Bytom mine site (Ilieva *et al.*, 2019). This analysis help us to define the need of tuning the modelling parameters and also to perform some test of a solution based on the more dense in time (every 6-days) DInSAR results instead of the levelling measurements performed 2 to 12 times per year (Figure 4).



a)

b)

Figure 4. Example of a profile through a subsidence bowl in the area of Bytom mine (USCB) for the period between March and October 2017 (two levelling cycles). The black line present the subsidence measured by levelling, the blue – by DInSAR, red line is the modelled subsidence calculated after Knothe-Budryk theory: a) Based on levelling data; b) Based on DInSAR data.

B. *Machine Learning approach*

Within the second project – EPOS-PL+, we are developing further the concept of using DInSAR surface deformation maps as the input values in the Knothe-

Budryk function for subsidence prediction. We apply a Feedforward neural network (FNN) by creating a set of parameters for each pixel from the deformation maps and from the plans for coal extraction. We used 80 % from the resulted about 300'000 vectors for the set of deformation maps between 2017 and 2021 as training data, while the rest are used for validation and as final testing data (Figure 5).

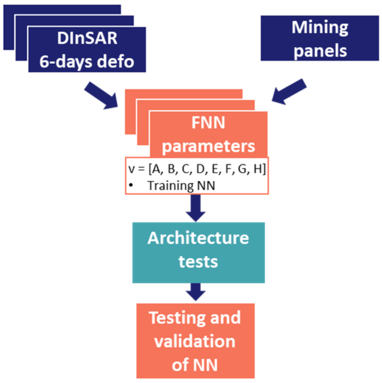


Figure 5. Scheme of the Machine Learning approach under development for subsidence prediction within EPOS-PL+ project.

IV. RESULTS

Within the two projects EPOS-PL and EPOS-PL+ we used a set of freely available SAR data provided by ESA on the Sentinel data hub Sentinel-1 A&B radar images (https://scihub.copernicus.eu/). At the moment the entire set of the ascending (No 175) and descending (No 051) Sentinel-1 data over USCB for the period 2016-2021 are processed. We used the ESA's platform for processing of Sentinel-1 interferometry – Sentinel Application Platform (SNAP), the Shuttle Radar Topography Mission (SRTM) 1 arc second (30 m resolution) Digital Elevation Model (DEM; Jarvis, 2008) for topographic phase removal, the Goldstein filter (Goldstein and Werner, 1998) for reducing the noise in the wrapped interferograms, and the minimum cost flow (MCF) function for phase unwrapping (Chen and Zebker, 2000). In CIBDS we are developing an automation of the SNAP consecutive processing that can ensure the regular production of deformation maps. We are also developing the automation and improvement of the post-processing approach for correcting the deformation maps described above. Here we present an example of an interferogram over the entire area of MUSE1&2 with the original product, the surface built by interpolation of the LOS displacement values for the locations of the most coherent pixels, and the corrected displacement map – Figure 6.

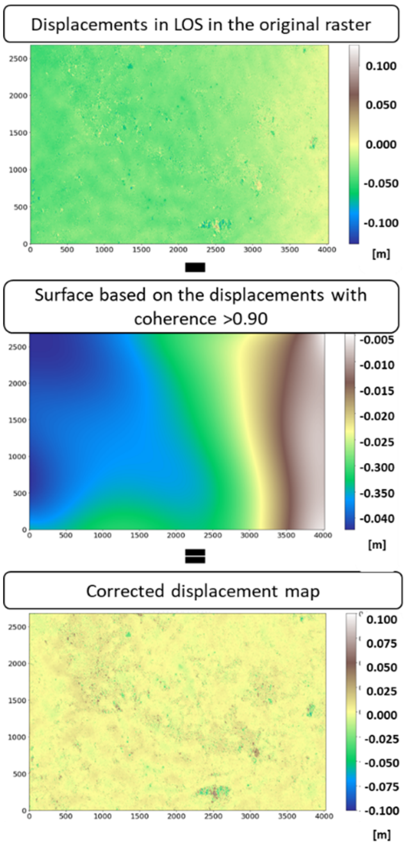


Figure 6. Example for correction of original deformation map as a product of SNAP DInSAR processing (up), the trend surface built from the pixels with stable coherence within 1 year (middle) and corrected displacement map (bottom).

For the needs of EPOS-PL and EPOS-PL+ partners we also produce 3 and 12-month cumulative subsidence maps. Here, the several of the yearly solution for MARCEL test site are presented in Figure 7.

For verifying the results of the DInSAR technique we build a geodetic network of benchmarks in the area of the MARCEL test site, where already two cycles of measurements have been performed (November 2021 and April 2022). Since at the moment of preparation of this report the second cycle of data are just measured but not processed we present the network of the measured levelling lines and an example of the total cumulative 3-years vertical displacements along one of the lines (Figure 8). For the estimation of the vertical component we combined the data from ascending and descending orbit tracks, with assumed north component of the displacement as negligible. After processing of the measurements of the second campaign, we will apply the north component from the GNSS measurements to the 3D decomposition solution.

V. CONCLUSIONS

We present an improved method for post-processing of DInSAR deformation maps, based on a trend removal approach aiming to reduce the atmospheric artefacts, the orbital ramp and minimize the unwrapping uncertainties in each deformation map. In addition we perform statistical quality assessment and detection of the images with lower quality. The goal is to reduce the outliers in the DInSAR time series, that can give, firstly more precise values for the dynamics of non-linear surface displacement in the mining area of USCB, and secondly more reliable data for mining management and prediction modelling. Within the new phase of the Polish realization of EPOS initiative we, in CIBDS, are developing also a methodology for subsidence prediction based on Neutral network approach, using the products of the improved DInSAR processing.

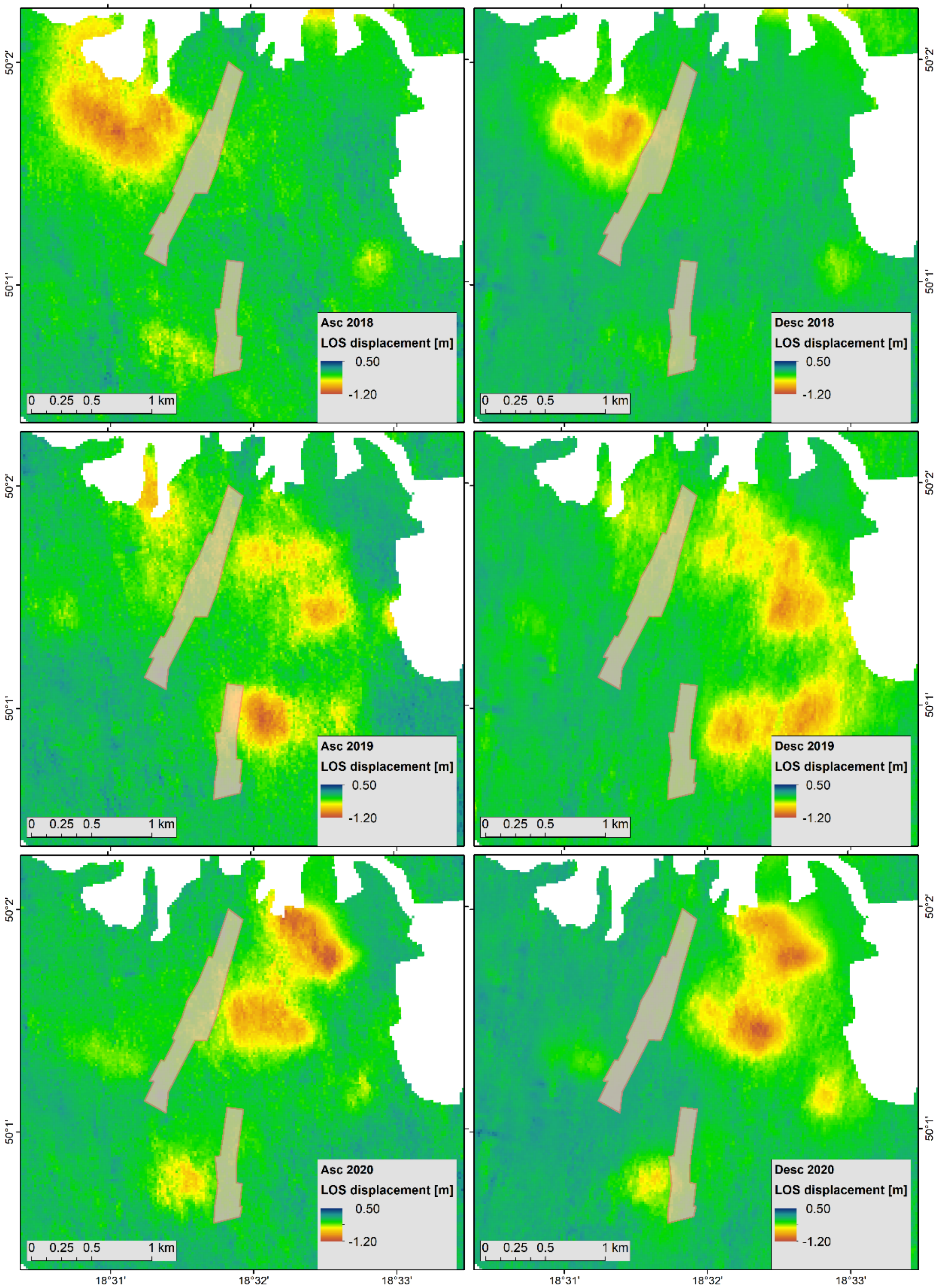
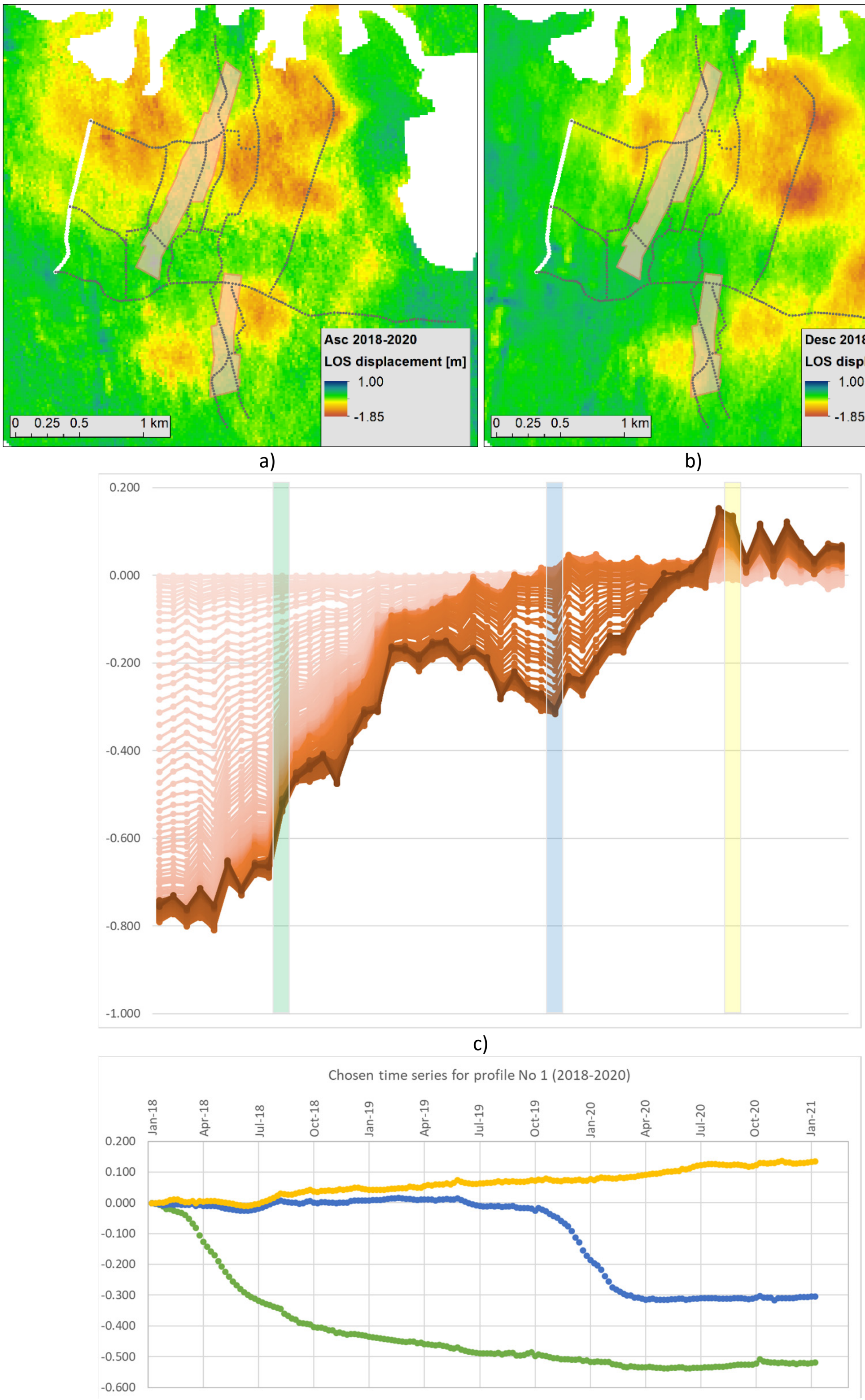


Figure 7. Yearly dynamics of the surface deformations in the area of MARCEL test site in USCB – generated from ascending (“Asc”, left column) No 175 and descending (“Desc”, right colomn) No 051 Sentinel-1 orbits for the years 2018, 2019 and 2020. The polygons present the location of two underground safety pillars. The Corine Land Cover (version 2018, © European Union, 2018) polygons are used to mask the densely vegetated areas (in white).



a) b)

c)

d)

Figure 8. Ascending a) and Descending b) cumulative subsidence for the period 2018-2020 for the area of MARCEL test site with the location of the safety pillars (red polygons) and the levelling network (black dots). The white dots represent the benchmarks from the levelling line used as an example of cross-section through the cumulative DInSAR vertical deformation maps (c), that was estimated as a 3D decomposed solution from the 6-days ascending and descending LOS displacements. d) present the time-series of chosen points – the colours correspond to the point shown with the same colour in the profile above c).

Still we need to accomplish several tasks like the full 3D-decomposition of the deformation maps produced in the LOS, including implementation of the horizontal component from GNSS measurements, defining the best approach for filling bigger gaps of rejected data with lower quality, and to develop an integration of more external information in the modelling algorithm.

VI. ACKNOWLEDGEMENTS

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