Review of SAR based deformation monitoring case studies related to the development of Hungarian Ground Motion Service (HGMS)

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Summary

In this paper I presented case studies related to the development of the Sentinel-1 based Hungarian Ground Motion Service (HGMS). I discussed the applied materials and approaches. Regarding this, I demonstrated the capability of conducting AZPO, 2.5D DInSAR, PSI and SBAS analyses as well. According to such case studies, I investigated the co-seismic field of the 2020 Petrinja and the 2023 Eastern-Turkey Earthquake Sequences. Next, the mining and/or heavy industry related examples in neighboring countries are investigated. Besides, I also highlighted application of the technology over red-mud reservoirs related to the Neszmély case-study. Later, I presented the ESA funded utilization and integration of the derived results to the kinematic height reference scoped INGRIM project.

Keywords: Sentinel-1, InSAR, PSI, SBAS, Hungarian Ground Motion Service

A műholdradar-alapú Magyarországi Mozgásvizsgálati Rendszer (HGMS) fejlesztéséhez kapcsolódó esettanulmányok áttekintése

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Összefoglalás

Jelen cikkben bemutatom az LTK-KGO Magyarországi Mozgásvizsgálati Rendszerének (HGMS) fejlesztéséhez kötődő esettanulmányokat, mérföldköveket. Ennek során kitérek a felhasznált Sentinel-1 adatok és alkalmazott eljárások bemutatására, melyek implementálása a kapcsolódó kutatás-fejlesztési tevékenységnek köszönhetően valósult meg, és már az LTK-KGO rendelkezésére állnak. Demonstráltam az Azimuth Pixel Offset Tracking (AZPO) módszert a 2023-as kelet-törökországi földrengéssorozat elemzése kapcsán, valamint a 2.5D DInSAR eljárást a 2020-as horvátországi petrinyai földrengéssorozat koszeizmikus deformációs mezőjének meghatározásánál. Ezt követően fejlettebb Persistent Scatterer Interferometry (PSI) eljárással végzett Interferometric Point Target Analysis (IPTA) elemzéseket mutattam be több, mozgásvizsgálati célú elemzés eredményei alapján. Elsőként a Magyarország–Szlovákia–Románia–Ukrajna határ menti régiójára végzett GeoSES (HUSKROUA/1702/8.1/0065) projekt keretén belül levezetett műholdirányú deformációs mintákat mutattam be a kárpátaljai Aknaszlatina (UKR), az erdélyi Nagybánya (ROM), valamint a felvidéki Nagyida (SLK) mintaterületek esetében, melyek bányaműveléssel és/vagy nehézipari tevékenységgel érintettek. Ezt követően demonstráltam a technológia alkalmazhatóságát olyan vörösiszap-tározó esetében, melynél a PSI-eljárás nem, vagy csak részben adott teljes képet az ipari objektum mozgásvizsgálati jellemzőiről. Ennek során ismertettem a Neszmélyi VIII. számú vörösiszap-tározóra végzett InSAR-alapú mozgásvizsgálati eredményeket, LOS szinten. Az elemzés fő megállapításai a következők voltak: 1. a fluidfrakcióval terhelt tárolókazettához közeli tárolószakaszokat jelenleg is recens deformációs minta jellemzi, 2. ezen deformációs minta a fluidfrakciótól, valamint a teljes tározó hossztengelyétől távolodva csökkenő mintázatot mutat, 3. az északi zárógát területére eső térben aggregált mérési pontokban (tehát nem állandó szórópontban) a teljes mérési időszak 2022. januártól kezdődő időszakában a korábbi trendhez képest eltérő változást sikerült kimutatni, amely abszolút értelemben 5–10 mm LOS irányú elmozdulással jellemezhető – ennek oka ez idáig nem tisztázott. Végezetül átnézeti képet adtam a HGMS fejlesztéséről és közvetlen gyakorlati alkalmazásáról: a HGMS eredményeinek integrálása megtörtént az ESA által finanszírozott „INGRIM: Integrated Galileo reference infrastructure and technology development for height modernization" (4000138838/22/NL/RR) projektbe. A projekt kinematikus magassági referenciamodelljének térbeli rövid és közepes hullámhosszú deformációs sebességeit a HGMS szolgáltatja. Kéziratomat egy rövid kitekintéssel és biztonságtudományi fókuszú diszkusszióval zárom.

Kulcsszavak: Sentinel-1, InSAR, PSI, SBAS, Magyarországi Mozgásvizsgálati Rendszer (HGMS)

Forewords

The use of the interferometric synthetic aperture radar (InSAR), the persistent scatterer interferometry (PSI), and the differential InSAR analysis (DInSAR) satellite techniques are currently the most modern and promising research methods for observing surface movements in geodesy and earth sciences. The author of this paper created the computational background necessary for the application of these methods, prepared new algorithms for processing the data provided by the satellites. He demonstrates the practical applications of these satellite techniques through various useful applications, which are also related to the development of the Hungarian Ground Motion Service.

According to case studies, he investigated the co-seismic field of the 2020 Petrinja Earthquake Sequence, the 2023 Eastern-Turkey Earthquake Sequence, as well as the surface deformations caused by the Ukrainian salt mines related examples and its related deformation patterns. He also prepared a very important study related to the deformation monitoring InSAR analysis of the Neszmély red mud reservoir. All of these examples demonstrate the excellent application potential of the satellite technique under consideration and the effectiveness of the author's work.

In my opinion, the results of Bálint Magyar are very significant, the method developed by him points out that the applied technology has a huge potential in natural hazard monitoring, especially related to ground motions (subsidence or rises) and to other ground deformation problems.

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The technologies based on satellite radar interferometry (InSAR) are providing unique and capable tools to precisely monitor displacements on the Earth surface. In security management and risk assessment the information about the status of the built environment and ongoing processes in rural territories as well are hardly achievable with other technique as InSAR at that high resolution and accuracy level. The efforts of Bálint Magyar in the frame of the KDP supported project will lead soon to publishing a high resolution surface displacement map of Hungary. This map already incorporating the GNSS velocity model produced by the Satellite Geodetic Observatory (SGO) will certainly be a basis for numerous studies and analysis in specific regions, or smaller scale settlements, almost down to single building level. This paper is about to present the main application fields, where InSAR can be efficiently implemented. The analysis and interpretation of the 2020 Petrinja earthquake sequence, the stability investigation of the Neszmély red mud reservoir or the still sinking settlements around the Ukrainian salt mines are perfect examples for supporting that InSAR is a uniquely valuable and irreplaceable tool in modern risk management. The database and service, which will be refreshed and maintained over long term will certainly be a unique information source of other services and may be used by authorities to help them identify risk sources, issue warnings when necessary. SGO is proud of hosting this research in the frame of our R&D activities and we will also be happy to accommodate our new service of Hungarian InSAR Ground Motion Service.

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Introduction

Monitoring and mapping natural and anthropogenic deformation patterns affecting our environment has an important role to mitigate and/or prevent the related natural hazards. Such activities are not just focused by the scientific and engineering community, but also may be in the interest scope of the local/regional authorities as well. Interferometric synthetic aperture radar (InSAR) is one of the quickly developing active remote sensing techniques, which is also capable of detecting mm-scale deformation patterns and providing solutions even for regional spatial and multi-annual temporal scales in measurement points with high spatial density.

The physical characteristics of the technology, e.g. the atmosphere, are transparent in the investigated wavelength, make weather and daytime independent Earth observation possible. In general, the technology utilizes the phase information of complex synthetic aperture radar (SAR) images taken over a period of time, between one or multiple repeated acquisitions. In each pixel of the SAR acquisition, relative phase differences occur between two or more acquisition times, which may be converted to satellite line-of-sight (LOS) deformation after removing the non-deformation related phase terms *(Boncori 2019; Constantini et al. 2009; Ferretti–Prati–Rocca 2001; Pepe–Caló 2017; Werner et al. 2003; Wegmüller et al. 2016)*.

The Satellite Geodetic Observatory of the Lechner Nonprofit (LTK-SGO) in Penc started the development of a service in which InSAR-based deformation field provides a comprehensive overview of deformation affected infrastructure in Hungary. The characteristics of such a service aim to optimize the end-user utilization of the technology at different interpretation levels, from the civilian usage to the scientific/engineering interests as well. In this article, I provide a brief review of the main case studies which are related to the development of the ongoing Hungarian Ground Motion Service (HGMS), and also which contributed to the realization of HGMS.

Materials

As the main input data of the InSAR analysis, I used the interferometric wide swath mode of Sentinel-1A (S1A) and Sentinel-1B(S1B) TOPS (Terrain Observation with Progressive Scanning) level-1 *(Yague-Martinez et al. 2016; S1PRD 2020)* acquisitions. Regarding the input dataset, I analyzed the Level-1 Single Look Complex (SLC) datasets of S1AB, namely a focused and georeferenced SAR data with zero-Doppler orientation in slant-range or radar Doppler coordinate (RCS) geometry. These C-band Single Look Complex (SLC) *(Yague-Martinez et al. 2016; S1PRD 2020)* IW mode datasets with VV polarization have been utilized and accessed via the Alaska Satellite Facility *(ASF 2023)*.

Taking advantage of the 6-day revisiting time of the S1AB mission, regional deformation mapping can be performed with short temporal baselines of 6 days and 12 days. Additionally, auxiliary input data is also utilized, namely the POD (Precise Orbit Determination) Precise Orbit state vectors of the Sentinel-1 mission, provided by Copernicus Data Space Ecosystem (CDSE) *(S1POD 2020; CDSE 2023)*. Additionally, 1 arc-sec input Digital Elevation Model (DEM) *(EROS 2018)* is also integrated into the processing workflow.

To implement the described workflow, I used the LTK-SGO licensed GAMMA Remote Sensing Software *(Wegmüller et al. 2016)*. Workflow development and co-developed solutions are realized within the Anaconda Scientific Programming environment. For visualization purposes, OSM, Google Earth and ArcGIS World Imageries as basemap solutions are utilized.

Methods

As also discussed above, InSAR utilizes the relative phase differences of complex synthetic aperture radar (SAR) images taken from the same acquisition geometries, over a period of time, between one or multiple repeated acquisitions. It is important, that interferometric analysis requests high phase stability and/or quality which makes the interferometric signal interpretable compared to the temporal and spatial decorrelation affected parts of the signal. Such can be obtained either via interpreting the interferometric signal in coherent or persistent scatterer points which preserve the resolution of the dataset, or through applying spatial filtering or spatial aggregation of the data, which improves the coherence of the data while it may reduce its spatial resolution or high frequency spatial characteristics of the dataset. According to the development of HGMS, I investigated multiple approaches of InSAR processing techniques, as well as developed the capabilities of LTK-SGO to perform such tasks.

Differential InSAR

First, the simple 2-pass differential InSAR analysis (DInSAR) for a given relative orbit has been implemented. This approach utilizes two SAR images with two different acquisition times. To form the differential interferometric phase field from the input data, preprocessing steps shall be taken before the analysis. Such steps include the addition of precise orbit state vectors (PODs) to the dataset, as well as importing the a priori digital elevation model into RDC geometry. For such geocoding process, the offset tracking-based intensity cross-correlation enhanced terrain-lookup table approach has been realized *(Frey et al. 2012; Strozzi et al. 2002; Wegmüller et al. 2016)*, with optimized parameter set *(Magyar et al. 2022b)*. Following this, the sub-pixel level relative resampling, namely coregistration of the SAR images is performed on the two SAR acquisition pairs *(Schreiber–Moreira 2000; Wegmüller et al. 2016; Xu et al. 2020)*. After this step it is possible to form the complex interferometric phase field from the SAR images, although the related phase field is wrapped between $\pm\pi$ radians and contains all phase components. To deliver the complex differential interferometric phase field of DInSAR analysis, it is necessary to simulate and subsequently subtract the phase components related to topography and orbit configuration. One of the key steps of any InSAR analysis workflow, is the proper phase unwrapping of the interferometric phase, which is only known by 2π modulo *(Constantini 1998; Esch et al. 2017; Goldstein–Zebker–Werner 1988; Werner–Wegmüller–Strozzi 2002; Wegmüller et al. 2016)*. To retrieve deformation related information it is necessary to add a proper multiple of 2π, similar to solving the GNSS phase ambiguity problem *(Paláncz–Völgyesi 2020)*. Solving the 2D phase unwrapping problem, I applied the Minimum Cost Flow algorithm (MCF) with successive shortest path (SSP) realization method on an irregular triangular mesh *(Wegmüller et al. 2016)*. After the successful unwrapping step, it is possible to derive the displacement field occurring between the two acquisition dates relative to a spatial reference point (SRP). The resulted deformation field is interpreted along the 1D Line-of-Sight (LOS) vector. Generalized DInSAR approach for a given relative orbit is visualized in the top panel of *Figure 1*.

The two types of relative orbit types of the used quasi-polar and right-looking SAR mission configuration of S1AB are also highlighted in Figure 1, namely the Ascending (ASC) and Descending (DESC) relative orbit directions. While a single DInSAR analysis from a selected relative orbit could measure deformation along the 1D LOS vector from an interferogram formed between two acquisition times, then the related physical interpretation is usually non-trivial, or requests special assumptions (e.g. assumption of all deformation is vertical). Thus, observing the same target from multiple geometries and relative orbits permits the decomposition of LOS deformations into East–West and Vertical displacement components, while the North–South component is neglected due to the low-sensitivity of the quasi-polar acquisition geometry of the SAR mission *(Boncori 2019; Manzo et al. 2006; Werner et al. 2003; Pepe–Caló 2017; Fuhrmann–Garthwaite 2019; Fujiwara et al. 2000; Wang & Jónsson 2015; Wegmüller et al. 2016)*. The above described method serves as the *basic concept* of differential interferometric deformation mapping, although it is limited by artefacts, e.g. like decorrelation and atmospherics delay, thus many more advanced processing approaches also exist *(Boncori 2019; Constantini et al. 2009; Manzo et al. 2006; Ferretti–Prati–Rocca 2001; Werner et al. 2003; Pepe–Caló 2017)*.

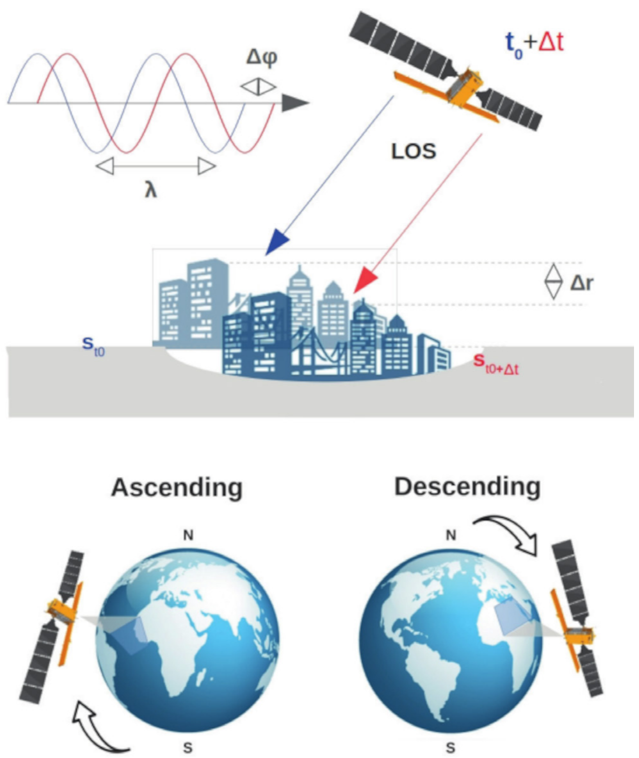

Figure 1 Top panel: 2-pass DInSAR basics (initial acquisition time: t_0, subsequent acquisition time: Δ_t, LOS: line-of-sight direction, undeformed surface: st_0, deformed surface $s_{t0+\Delta t}$, Δφ: relative phase difference). Bottom panel: visualization of the ASC/DESC orbits

Source: Magyar, 2022

Persistent Scatterer Interferometry (PSI)

To perform deformation mapping and monitoring for HGMS, I primarily analyzed a set of interferograms in a framework of multi-interferogram approach of Persistent Scatterer Interferometry (PSI) *(Constantini et al. 2009; Ferretti–Prati–Rocca 2001; Werner et al. 2003)* via the workflow of Interferometric Point Target Analysis (IPTA) *(Werner et al. 2003; Wegmüller et al. 2016)*. Thus, the analysis is focused on coherent scatterer targets and compensates several phase contributions, like atmospheric phase screen (APS), to estimate deformation rates and displacement histories of the investigated data, using both ASC and DESC SAR datasets.

To perform multi-annual deformation monitoring, I determined a list of Permanent Scatterer Candidates (PSCs) *(Constantini et al. 2009; Ferretti–Prati–Rocca 2001; Werner et al. 2003; Wegmüller et al. 2016)* in three main steps. First, I applied the spectral diversity approach to identify the set of points of coherent point targets in the spectral domain of each layer of the stack of the coregistered single-look complex (RSLC geometry) SAR acquisitions. Second, to also consider the multi-temporal criteria of phase stability in temporal domain, I derived a list with low temporal variability of the RSLC intensities. Third, the number of determined PSCs is also reduced during the subsequent IPTA analysis *(Werner et al. 2003; Wegmüller et al. 2016)*.

As discussed earlier, InSAR is a relative technology, so defining a spatio-temporal reference which serves as a basis for the relative deformation measurement is obligatory *(Constantini et al. 2009; Ferretti–Prati–Rocca 2001; Ferretti–Passera–Capes 2023; Werner et al. 2003; Wegmüller et al. 2016)*. There are two common approaches which can be utilized: selecting a physical spatial reference point (SRP) from the set of PSCs, considering its physical characteristics; or to define a virtual reference point which is derived through some data generalization steps *(Ferretti–Passera–Capes 2023)*. While, both approaches have advantages and disadvantages, we selected the physical spatial reference point approach during the applied analysis. The reason behind our choice is twofold. First, using physical reference point aims the spatial referencing of the relative deformations to an actual physical measurement point. Second, this point can be delivered by considering its temporal and spectral characteristics, namely a point with stable interferometric phase, which also minimizes the spectral decorrelation.

Regarding the temporal referencing of the investigated dataset, two possible setups were investigated, namely the multi-reference and single-reference multi-baseline approaches. While the single-reference approach has a dedicated spatio-temporal reference SAR acquisition (all interferograms formed respect to this reference), then the multi-reference approach does not have such reference and solves the interferometric analysis through a redundant spatio-temporal baseline network, similarly to SBAS approaches. The latter one is different from SBAS in the sense that it is interpreted in PSI targets (thus in full resolution) instead of spatially aggregated and filtered data format. While PSI is excellent to monitor the long-term deformation history of built-up infrastructure, SBAS exploits the short temporal separation of the short temporal baseline acquisitions, which minimize the related spatio-temporal decorrelation, making it a proper approach to perform large scale deformation mapping for areas with sparse vegetation, even not in full spatial resolution.

Interferometric Point Target Analysis (IPTA)

As previously highlighted, one of the key steps of the InSAR analysis is the proper phase unwrapping. During the PSI analysis we applied linear phase unwrapping approaches, namely 2D spatial and 1D temporal phase unwrapping methods *(Constantini 1998; Esch et al. 2017; Goldstein–Zebker–Werner 1988; Hanssen–Teunissen–Joosten 2001; Werner–Wegmüller–Strozzi 2002; Werner et al. 2003; Wegmüller et al. 2016)*. While the 2D phase unwrapping is presented above, regarding the temporal 1D phase unwrapping, I modeled the dependence of the differential interferometric phase relative to the spatial reference point (SRP) with respect to perpendicular baseline, also linear deformation rate (as first order deformation approximation) and height *(Werner–Wegmüller–Strozzi 2002; Werner et al. 2003; Wegmüller et al. 2016)*. Such 1D phase unwrapping involves the minimization of the residuals in least-squares (LSQ) sense between the observed and modeled phases during the regression analysis *(Werner–Wegmüller–Strozzi 2002; Werner et al. 2003; Wegmüller et al. 2016)*. Combined application of such phase unwrapping approaches aims at the effective unwrapping of spatially smooth phase terms, like atmospheric phase terms, and unwrapping in time also supports the unwrapping in case of low spatial coherence, especially after the initial atmospheric phase screen (APS) removal. Although the process is optimized for linear deformation patterns/processes, slight non-uniform movement can be also dealt with, if the non-uniform deformation phase term does not impact/disturb the wrapping process *(Ferretti–Passera–Capes 2023; Werner et al. 2003; Wegmüller et al. 2016)*.

After obtaining the PSC list, we performed Interferometric Point Target Analysis (IPTA) *(Werner et al. 2003; Wegmüller et al. 2016)* to keep permanent scatter (PS) points with decent phase stability from the initial PSC list and interpret the different phase terms. The goal of this complex step is to model and compensate different phase terms which may affect the scene to derive the related deformation history and to identify and model each phase term present in the differential interferometric phase (e.g. atmospheric, baseline-dependent, height-dependent, deformation, etc.) *(Werner et al. 2003; Wegmüller et al. 2016)*. Following this, I sequentially re-conducted the same 2D regression analysis with respect to baselines and time intervals with extended and/or precursor corrections of the separated/modeled phase terms. Such corrections consist of: updated and multi-scale smoothed atmospheric phase term (including turbulent and stratigraphic phase terms; which are temporally not correlated but spatially correlated with low pass characteristics), linear deformation rate related simulated unwrapped phase and relative height correction related simulated unwrapped phase. Iterations involving the above described 2D regression analysis are done, while the resulting parameter sets became quite small or do not show improvement and the applied IPTA process converged. Note, that the derived parameters of linear deformation rates are not the final ones, but only serve as an interpretation factor during the phase unwrapping process and assure proper unwrapped solution (both the 2D+1D) *(Werner et al. 2003; Wegmüller et al. 2016)*.

Upon reaching converged IPTA process, the next step is to reconstruct the full unwrapped point differential interferometric or the unwrapped interferometric phase stacks. This can be realized via summing the derived and interpreted unwrapped phase terms discussed above. Following this, the simulated unwrapped phase terms of the different deformation components, including the phase noise/residuals are separately summed and submitted to a final 2D regression analysis without 1D phase unwrapping, to derive the final linear deformation rate estimations in Line-of-Sight (LOS) direction *(Werner et al. 2003; Wegmüller et al. 2016)*. Following this, the deformation related phase data stacks are converted to Line-of-Sight (LOS) deformation fields and displacement time-series, consisting of relative deformation data with respect to the selected physical and temporal reference point *(Werner et al. 2003; Wegmüller et al. 2016)*.

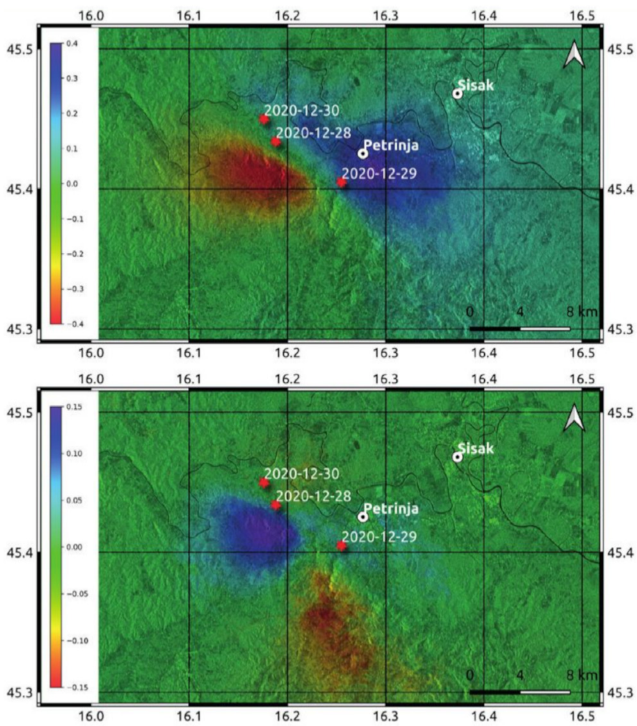

Figure 2 Co-seismic deformation field of 2020 Petrinja Earthquake Sequence. Top panel: East-West, bottom panel: Up-Down components derived from 2.5D DInSAR analysis

Source: Magyar, 2022

Results of case studies

In this section, I present case studies related to the above discussed methods, which occurred during the development of HGMS. While recently only the PSI approach is integrated into the service other methods also show future extension/upgrade potential, which are also present in the LTK-SGO as developed production workflow.

Petrinja 2020 Earthquake Sequence

Petrinja Earthquake Sequence occurred between 28 and 30 December 2020, when three earthquakes with magnitudes greater than 4.3 occurred near to the town of Petrinja in Croatia. To derive the related co-seismic deformation field, I analyzed both the available ascending and descending Sentinel-1A/B images preceding and following the Petrinja Earthquake Sequence via the 2.5D differential interferometric analysis method *(Fujiwara et al. 2000; Boncori 2019)*. Large scale mapping of co-seismic event related deformation field may have significant importance in civil engineering related countermeasures and hazard assessment. With the applied methodology, the derived horizontal and vertical deformation fields can be characterized by a maximum of ±0.43 m local East–West, a maximum of 0.15 m local subsidence and a maximum of 0.19 m local vertical uplift near Petrinja *(Magyar 2022)*. The local East–West and Vertical deformations are illustrated in *Figure 2.*

Eastern-Turkey / Nurdagi 2023 Earthquake Sequence

The 7.8 magnitude earthquake on 6 February 2023 and the subsequent series of strong aftershocks caused unprecedented losses in eastern Turkey and northern Syria. The event has strongly raised public awareness of the importance of plate tectonic processes and their social and economic risks. While the Earth's lithosphere is in a state of constant change, and large-scale plate tectonic processes of up to a few cm/year can be detected by a series of long-term GNSS measurements *(Kenyeres et al. 2019; Magyar et al. 2022a)*, but this process is well exceeded by these earthquakes and associated seismogenic deformations. Resulted deformation field can be highlighted by the implemented azimuth pixel offset tracking (AZPO) *(Boncori 2019; Strozzi et al. 2002; Wang–Jóns-*

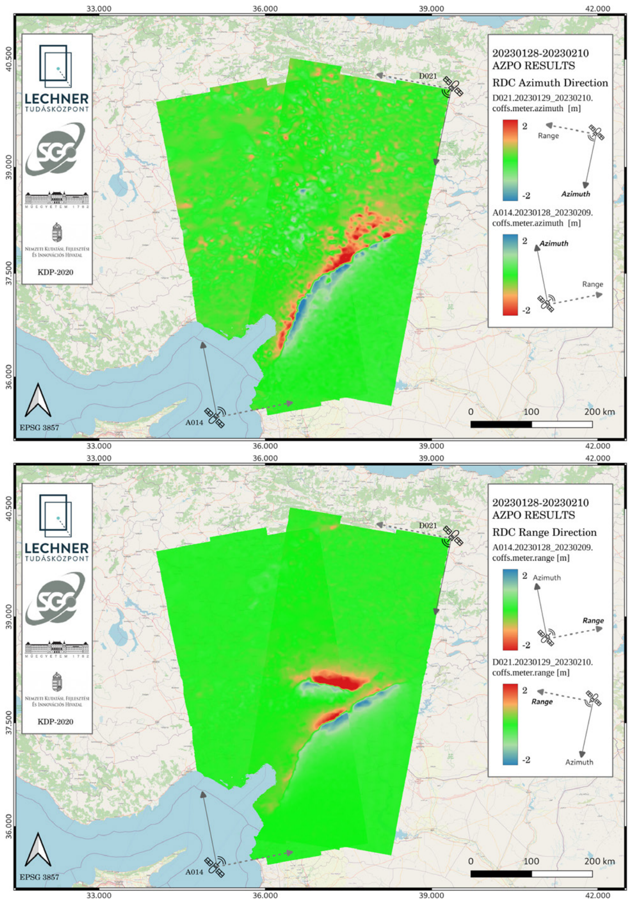

Figure 3 AZPO results of the 2023 E-Turkey Nurdagi Mainshock. Top panel: range offsets, bottom panel: azimuth offsets

Source: Kenyeres–Magyar–Juhász, 2023

son 2015) analysis. AZPO results of S1AB images show that the satellite's azimuth and range pixel offsets indicate a significant displacement field of several meters at the site of the earthquake, the red and blue pixels illustrate the areas affected by displacements as *Figure 3* illustrates *(Kenyeres–Magyar–Juhász 2023)*. The derived displacements in many cases exceeded 4 m in relative terms in these azimuth and range directions, and the main earthquake of 6 February (the southern red–blue anomaly) affecting Gaziantep and Hatay provinces and the subsequent northern anomaly caused by subsequent earthquakes in Kahramanmaras and Adiyaman provinces are clearly visible in the lower image *(Kenyeres–Magyar–Juhász 2023)*. While AZPO is not an interferometric technique, it only utilizes intensity information of SAR products, which makes it applicable in cases where the decorrelation significantly affects the phase field of the SAR acquisitions or there is a large scale and quick deformation phenomena in the research scope.

GeoSES Project

Within the Hungary-Slovakia-Romania-Ukraine (HU-SK-RO-UA) ENI Cross-border Cooperation Programme (2014–2020) "GeoSES" – Extension of the operational "Space Emergency System" (GeoSES) project (project number: HUSKROUA/1702/8.1/0065), one of the main objectives of the project was to investigate dangerous natural and anthropogenic geo-processes and aim at hazard assessment using space geodetic technologies and concentrating on the Hungary-Slovakia-Romania-Ukraine cross-border region. The monitoring of such natural hazards and emergency situations (e.g. landslides and sinkholes) have utilized ASC and DESC S1AB Level-1 SLC acquisitions since 2014 until 2021 over the indicated cross-border area, focusing on the Subcarpathian Region *(Magyar–Horváth 2022a, 2022b)*. After a preliminary (2019–2020) single-reference PSI analysis of two areas of interest *(Magyar–Horváth–Völgyesi 2021),* the multi-reference regional and long-term (2015–2021) PSI analysis highlighted several areas of interests (AOI), where deformation patterns occur concurrently *(Magyar–Horváth 2022a, 2022b)*. *Figure 4* illustrates three related example cases, where deformation is interpreted along 1D DESC LOS vectors. Top panel of *Figure 4* highlights the deformation pattern of collapsing salt mine vaults in Aknaszlatina in Subcarpathia, Ukraine. The deformation pattern indicates that some industrial blocks are affected by even more than –15 mm/year LOS displacement rate. Nearby the sinkholes, a residential block is also endangered by recent deformations of –3–4 mm/year. Middle panel indicates the Nagybánya AOI. Bottom panel shows the example of the village of Nagyida in Slovakia, and the U.S. Steel Kosice heavy industrial plant and its related landfill/tailing piles. The mass-movements and/or compaction of the landfill/tailing piles indicates strong uniform and non-uniform movements (even >10 mm/year) as well, which may raise environmental concerns, because such movements, especially at the sides of tailing files, could increase the exposure and erosion of the already dumped byproducts of industrial activity, such could increase the related contamination transport to the vicinity.

Neszmély VIII Red Mud Reservoir

I performed the deformation monitoring scoped InSAR analysis of the Nr. VIII. Red Mud Reservoir of Neszmély. The applied approach was the vectorized SBAS method, where the interferograms were formed within a triple-redundant spatio-temporal baseline network. After the preprocessing steps and the applied spatial aggregation and filtering (30m × 30m kernel window), the input raster data were vectorized, and also thresholded by averaged multi-temporal coherence after forming the differential interferogram stacks. Following this, I performed the above described IPTA analysis for both A175 and D051 S1AB data in the 2014 to 2022 period, with respect to a spatially aggregated point in the Eastern area of Neszmély, assuming spatially smooth APS window. The main reason for applying such an analysis was that the preliminary PSI analysis provided poor or no PSC coverage for the reservoir and the related artefacts. However, the applied vectorized SBAS approach provided interesting findings for the area of the reservoir, but also note that the results are derived from a spatially filtered and aggregated solution. Regarding this, the southern parts of the reservoir indicated recent deformation, especially in the reservoir unit closest to the fluid-fraction containing most southern reservoir part. The measured deformation field indicated the characteristic reduction of the average displacement rates along the reservoir longitudinal axis in South to North direction, starting from –30.4 [mm/yr] to –0.6 [mm/year] for the A175 multi-reference and multi-looked LOS solution, respectively. Characteristics of the average deformation rates along the quasi-South–North direction, as a transversal section of the reservoir, the D051 multi-reference and multi-looked LOS solution highlighted a –14.5 [mm/yr] to –20.8 and 18.9 [mm/yr] increase in the absolute sense towards the longitudinal axis of the reservoir; then indicated reduction of the absolute average LOS displacement rates from –18.9 [mm/yr] to –8.5 [mm/yr] along the same section towards the Eastern side of the reservoir area. Thus, it leads to the generalization that the derived LOS deformation field can be characterized with relatively high average deformation rate values (exceeding 20 [mm/yr] LOS deformation rates in this case) near to the fluid fraction or to the fluid fraction containing reservoir unit, and such deformation rates also show reduction pattern as moving away along the longitudinal and perpendicular axis of the reservoir, which may correspond to the behavior of the mud or to the related evapotranspira-

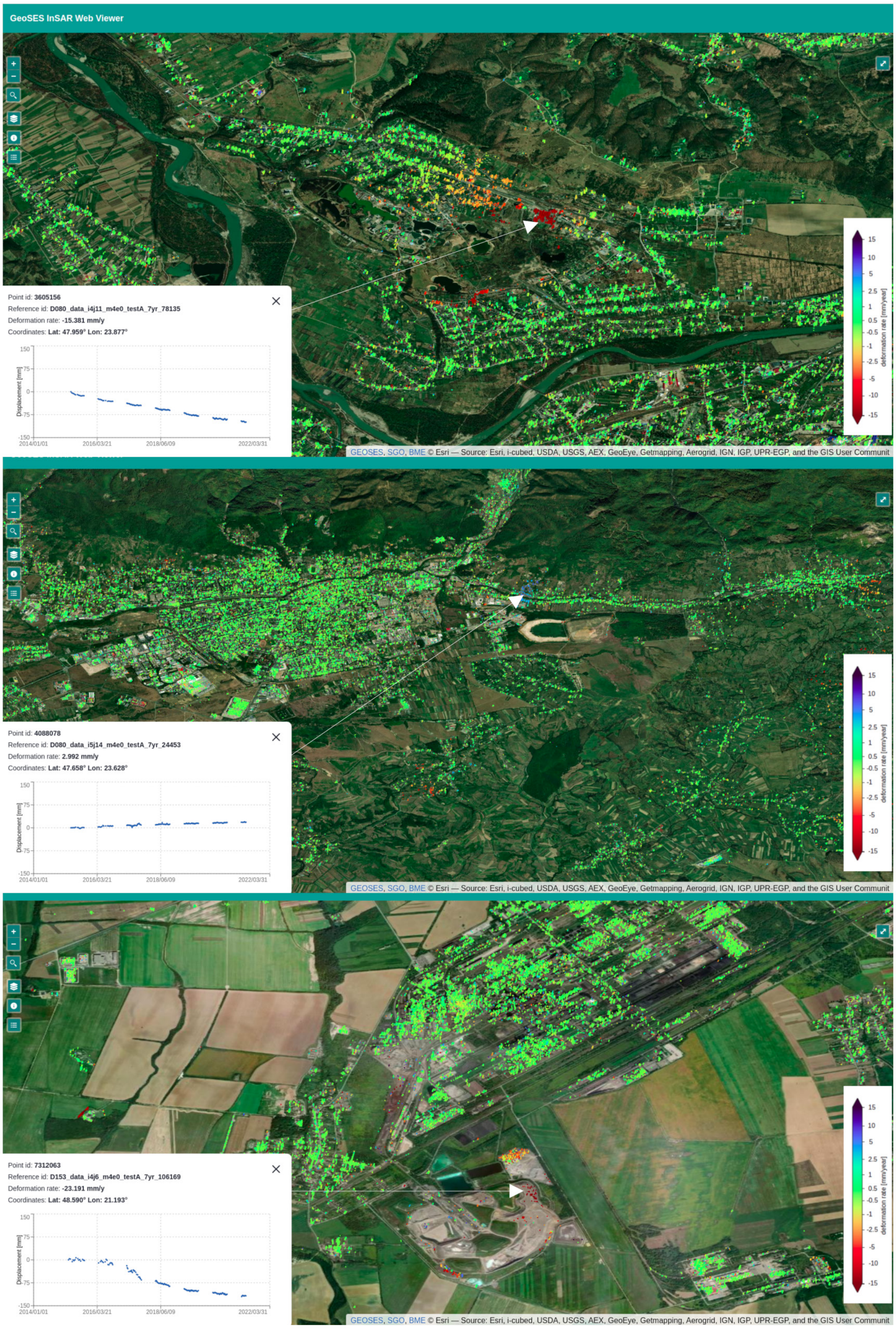

Figure 4 Multi-reference PSI descending LOS result examples of GeoSES project. Top panel: Aknaszlatina (UKR) AOI, middle panel: Nagybánya (ROM) AOI, bottom panel: Nagyida (SLK) AOI

Source: Magyar–Horváth 2022a, 2022b

tion, desiccation, compression and/or reservoir operational/re-cultivation processes, respectively. The derived A175 and D051 LOS results, as well as the described cross-sections are visualized in *Figure 5*.

Despite this, the derived multi-looked measurement points over the western and central part of the Northern dam, both for A175 and D051 highlighted different trends in the measurement time-series within the

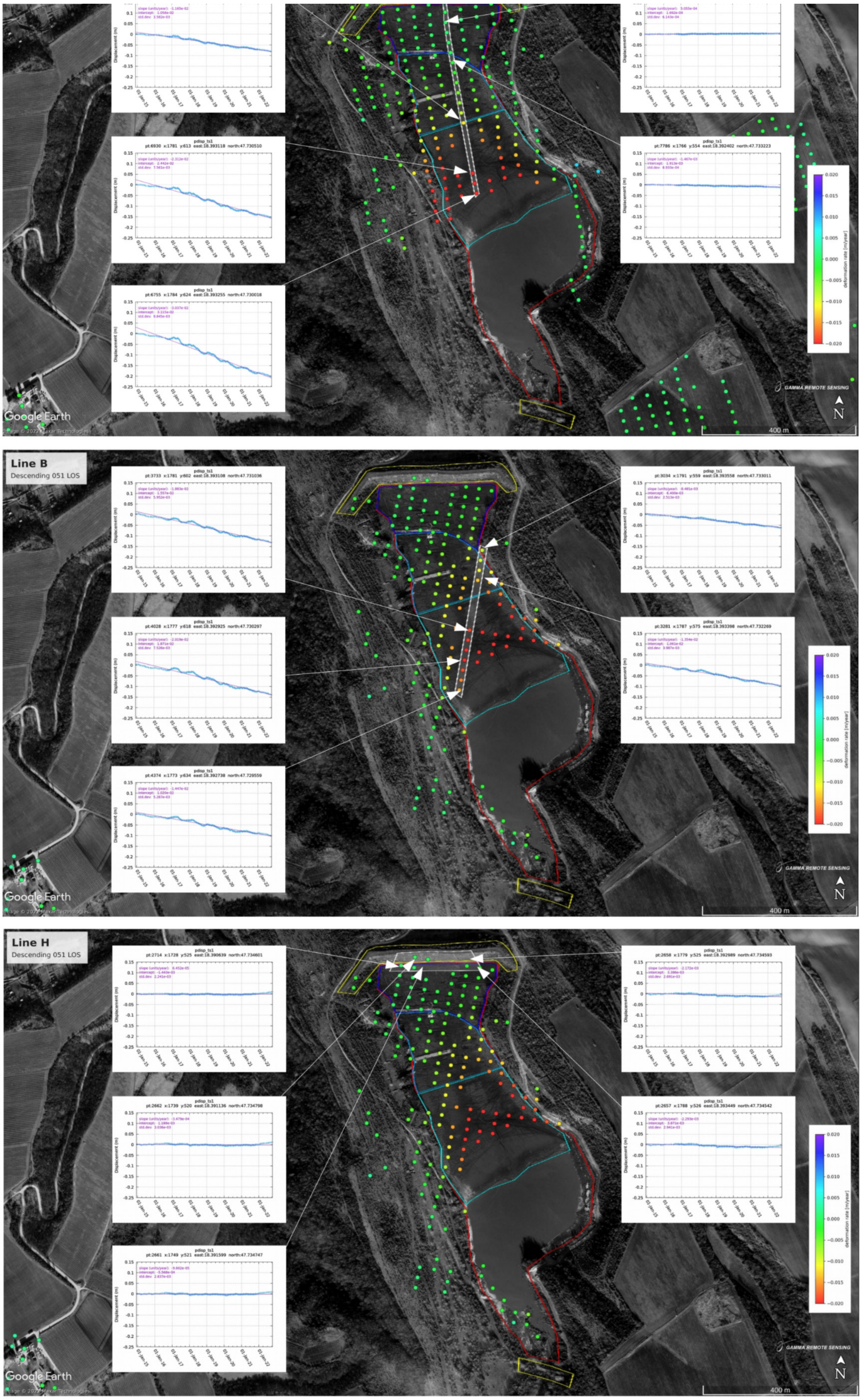

Figure 5 Multi-reference vectorized SBAS LOS result of the Nr. VIII Neszmély Red Mud Reservoir analysis. Top panel shows the A175 LOS results, middle panel indicates the D051 LOS results. Bottom panel visualizes the D051 SBAS LOS results over the Northern Dam, the indicated deformation histories covering 2022 are different than its preceding period

Source: Own work

January–November 2022 period compared to the preceding interval of the investigated time span. For the A175 LOS results, the average absolute displacement converges to or exceeds 5 [mm], while the D051 LOS results can reach up to 10 [mm] absolute displacement over the indicated artefact. The related deformation histories are visualized in the bottom panel of Figure 5. Such spatio-temporal deviations from the investigated time-series and their related linear model may raise environmental concerns, due to the closeness of the Northern dam of the Nr. VIII Red Mud Reservoir of Neszmély, although the cause of such phenomenon is not yet clarified for the measurement period in 2022.

HGMS and integrated INGRIM examples

As an outlook, the product development of HGMS is progressing well, and the implemented different interpretation levels aim at the broad scale dissemination and utilization of the HGMS results. The related most significant utilization so far is that the derived products are integrated and act as one of the key aspects of the ongoing ESA funded INGRIM (INGRIM: Integrated Galileo reference infrastructure and technology development for height modernization, 4000138838/22/NL/RR) project conducted by LTK-SGO. The goal of the project is to develop a high-added value product/service for survey engineers, geodetic professionals, civil engineers and earth scientists, which provides a kinematic height reference frame combining multiple technologies, like InSAR and GNSS *(Ferretti–Passera–Capes 2023; Del Soldato et al. 2021)*. HGMS is contributing to this product as delivering the spatial high and middle frequency deformation components of East–West horizontal and Vertical components in ETRF2000 reference frame, respectively *(Ferretti–Passera–Capes 2023; Del Soldato et al. 2021)*. The developed INGRIM and HGMS product/services were interacting with each other, so the integration of HGMS during its development phase to the

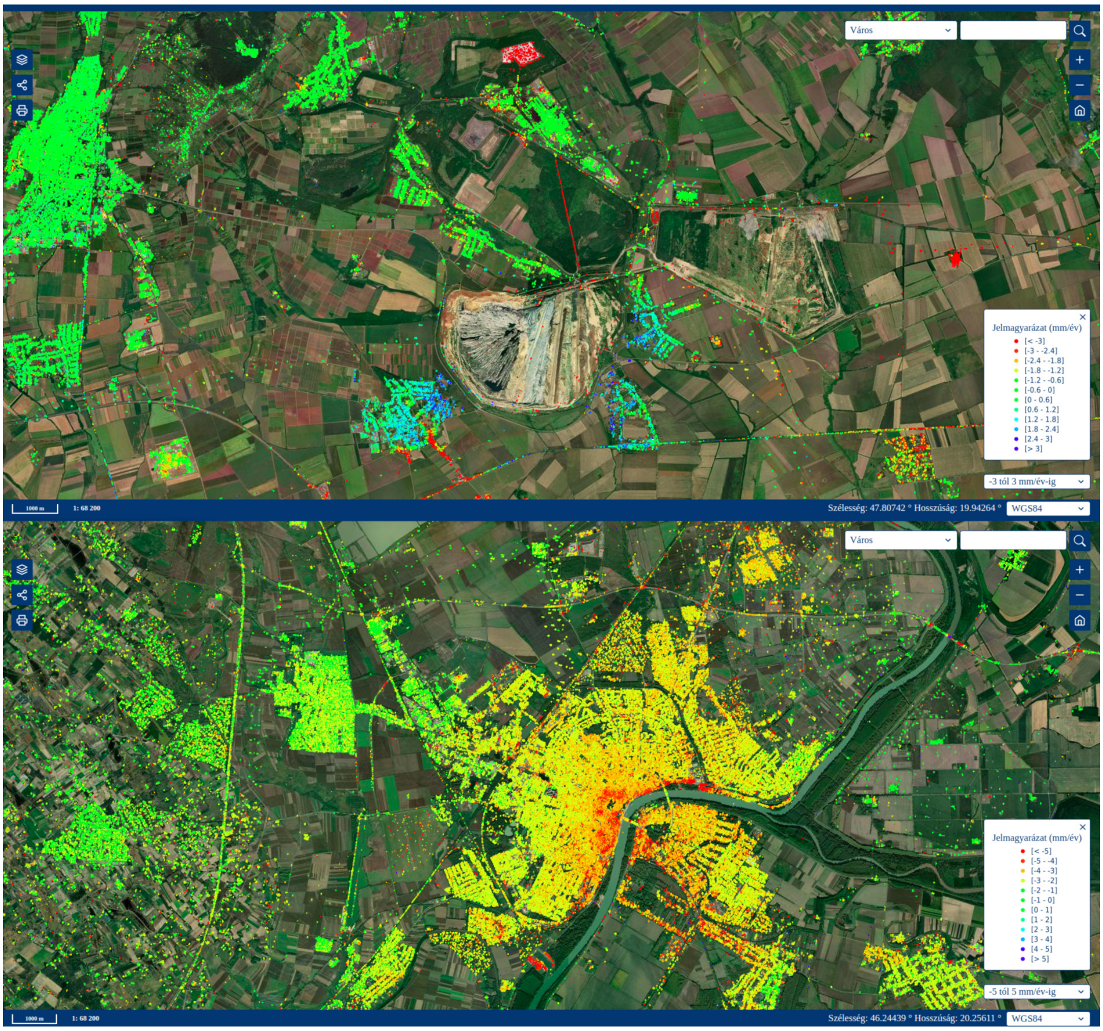

Figure 6 Development snapshots from Hungarian Ground Motion Service. Top panel indicates the DESC LOS field of Visonta–Halmajugra–Karácsond–Ludas–Detk AOI, bottom panel highlights the INGRIM related calibrated DESC LOS field of Szeged AOI

Source: Own work

INGRIM, has an overall positive impact on both resulting end products. INGRIM project is expected to be completed in 2024, as well as the release and publication of features of the developed HGMS. Some HGMS and INGRIM development snapshots are highlighted by *Figure 6*.

Conclusion

In this paper I presented case studies related to the development of the Hungarian Ground Motion Service (HGMS) provided by LTK-SGO. I discussed the applied materials, as well as the several applied approaches, that are already present in related product processing workflow at LTK-SGO. Regarding this, I demonstrated the capability of conducting AZPO, 2.5D DInSAR, PSI and SBAS analysis as well. According to such case studies, I investigated the co-seismic field of the 2020 Petrinja Earthquake Sequence, the 2023 Eastern-Turkey Earthquake Sequence, as well as the mining and/or heavy industry related examples and their related deformation patterns in neighboring countries, like in Aknaszlatina (UKR), Nagybánya (ROM) and Nagyida (SLK). Besides, I also highlighted the application of the technology over red-mud reservoirs related to the Neszmély case-study. Later, I presented the ESA funded utilization and integration of the derived results to the kinematic height reference scoped INGRIM project, where both product/service are expected to be completed in 2024. As the above examples indicated, the applied technology has a huge potential in natural hazard monitoring, especially related to subsidence and also to other deformation patterns. The related scope could be direct infrastructure monitoring, but deformation mapping of large area affected by the displacement can be also realized in a cost-effective way, benefiting the citizens of Hungary. According to this, further funding support and/or spatio-temporal upgrade of such deformation monitoring service at the LTK-SGO would be also beneficial for Hungary, due to the physical characteristics, which makes it an ideal candidate to perform long-term utilization of such ground deformation monitoring technology.

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