PRELIMINARY DATA ON LAND DEFORMATION TRENDS AT SLĂNIC PRAHOVA USING REMOTE SENSING DATA

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Abstract. Slănic Prahova has a complex geological setting, complicated by the salt tectonics, where numerous land deformations occurred in time and are periodically reactivated by heavy precipitation and earthquakes. The collapse of a portion of the road in the centre of the city in April 2024, which jeopardised the safety of the nearby inhabitants, led to intense research and monitoring in the area. Complex geological, hydrogeological, geotechnical and geophysical surveys were coupled with drillings and sensors for monitoring the evolution of land deformations in the affected area. In this paper, the methodology used to select some preliminary sites proposed for permanent installation of monitoring sensors is presented, based on the time series average velocities (2019–2023) measured by Synthetic Aperture Radar (SAR) sensors mounted on Sentinel-1 satellites, available on the European Ground Motion Service (EGMS). The data were compared with old photogrammetric surveys carried out in the 1970s and with field observations. The radar data, processed by the European Space Agency (ESA) using the interferometric technique, showed that the land movement at Băile Verzi (first site), Baia Baciului and Salt Mts. (second site) is continuing its downward trend. The third selected site is located close to the sinkhole which affected the road in Slănic in 2024. As archive photogrammetric surveys were not available for this site, the selection was based on SAR data and field inspections. It was demonstrated that EGMS products were useful for selecting the locations for the state-of-the-art sensors, which will continuously monitor various parts of the city of Slănic. It is proposed to use, when available, new time series radar data (2024 onwards), processed and delivered as EGMS products, to select the locations of the other sensors.

Keywords: radar, interferometry, photogrammetry, land deformation, EGMS.

Rezumat. Date preliminare asupra tendinţelor deformării terenului la Slănic Prahova utilizând date de teledetecţie. Slănic Prahova este situat într-un cadru geologic complex, complicat de tectonica sării, unde în timp au avut loc numeroase deformări ale terenului, care sunt periodic reactivate de precipitaţii abundente şi cutremure. Prăbuşirea unei porţiuni de drum din centrul oraşului în aprilie 2024, care a pus în pericol siguranţa locuitorilor din apropiere, a dus la cercetări şi monitorizări intense în zonă. Studii complexe geologice, hidrogeologice, geotehnice şi geofizice au fost cuplate cu foraje şi senzori pentru monitorizarea evoluţiei deformărilor terenului în zona afectată. În această lucrare au fost selectate câteva amplasamente preliminare propuse pentru instalarea permanentă a senzorilor de monitorizare, pe baza seriilor temporale de viteze medii (2019-2023) măsurate de senzorii radar cu apertură sintetică (SAR) de la bordul sateliţilor Sentinel-1, disponibili prin Serviciul European al Mişcării Terenului (EGMS). Datele au fost comparate cu ridicări fotogrammetrice mai vechi efectuate în anii 1970 şi cu observaţii de teren. Datele radar, procesate de Agenţia Spaţială Europeană (ESA) folosind tehnica interferometrică, au arătat că mişcările terenului la Băile Verzi (prima locaţie), Baia Baciului şi Muntele de Sare (a doua locaţie) îşi continuă tendinţa descendentă. Al treilea amplasament selectat este situat în apropierea dolinei care a afectat drumul din Slănic în 2024. Deoarece pentru acesta nu au fost disponibile date fotogrammetrice de arhivă, selecţia s-a bazat pe date radar SAR şi inspecţii pe teren. S-a demonstrat că produsele EGMS au fost utile la selectarea locaţiilor pentru senzorii de ultimă generaţie care vor monitoriza continuu diverse părţi ale oraşului Slănic şi se propune să se utilizeze, atunci când vor fi disponibile, date radar din serii temporale noi (începând cu 2024), procesate şi livrate ca produse EGMS, pentru alegerea locaţiei celorlalţi senzori.

Cuvinte cheie: radar, interferometrie, fotogrammetrie, deformări ale terenului, EGMS.

INTRODUCTION

Slănic (Prahova county) is well known for its salt exploitation, which began in the XVIIth century, in the time of Şerban Cantacuzino, the first mine being opened in 1689 (STAMATIU, 1943). Since then, salt was extracted in numerous mines, initially bell-shaped, then with a trapezoidal profile and nowadays with small chambers and rectangular pillars. At the half of the XXth century, Slănic had the most significant and most crucial salt mine in Romania (STAMATIU, 1942), a rank which was preserved to present day, the salt being also very pure (96-98% NaCl). The ceiling of old bell-shaped salt mines collapsed over time, and the cavities were filled with water, giving rise to the salt lakes Băile Verzi, Baia Baciului, Baia Miresii, etc. Due to the heavy precipitation regimes in some years, coupled with seismic events, the aspect, dimensions and salinity of the lakes suffered fluctuations. Slănic is situated in the East Carpathians Bend, belonging to the posttectogenetic cover of Tarcău nappe, consisting of molasse formations (HAR et al., 2006; SEGHEDI et al., 2021). Like in other areas in the East Carpathians Bend, numerous land movements were mapped in Slănic area, temporarily stabilised and reactivated after periods of abundant rain. CIOACĂ & DINU (2000) inventoried five categories of geomorphological processes in Slănic and assessed the volume of transported and deposited geological material. The largest volumes were for the category landslides (885 m^3 for transported material and 820 m^3 for deposited material in June 1998). The salt dissolution processes combined with earthquakes and landslides led to the final disappearance of Bride's Grotto and Salt Mountain in 2012, interesting geological sites and an attraction source for tourists. Moreover, the economy of the city began to decline as the therapeutic muds used for balneology in Baia Baciului and Băile Verzi started to lose their properties due to freshwater intake, over-exploitation, and failure to apply preventive measures or the lack of their effect.

The recent sinkhole that occurred in April 2024 on the 23 August St. was a result of a period of heavy rain that posed problems, as two nearby blocks of flats (approximately 60 families) were endangered. The local authorities, together with the Inspectorate for Emergency Situations, took necessary prevention measures and the sinkhole of 10 per 6 m, approximately 40-50 m deep, has started to be monitored by different remote sensing techniques (LiDAR, photogrammetry, satellite interferometry), geophysical techniques (electrometry, micro-gravimetry, seismics), hydrogeological and geotechnical drillings, as well as GNSS stations and accelerometers and inclinometers mounted on the buildings. There is an ongoing activity of the GEOMONITOR project *Integrated monitoring solution for natural and anthropogenic phenomena triggering societal risks, for the safety of the population in the affected area – Slănic city, Prahova County.* This project is led by the National Institute of Research and Development for Earth Physics (INFP), other partners in the consortium being the Geological Institute of Romania (IGR), the Faculty of Geology and Geophysics of the Bucharest University, the National Institute for Research and Development in the aero-spatial field "Elie Carafoli" (INCAS) and SIMAVI - Software Imagination & Vision S.R.L.

Given the interest of national and local authorities in this hazard-affected area and the present and future impact of the produced sinkhole on the well-being and welfare of the inhabitants, IGR decided to mount in five areas of interest in Slănic city the sensors developed within the InterReg project GeoNetSee *An AI/IoT-based system of GEOsensor NETworks for real-time monitoring of unStablE tErrain and artificial structures* financed through the Interreg Danube Region programme. These sensors will be permanently mounted in the selected locations, and they will record coordinates, using all satellite networks of the GNSS (Global Navigation Satellite System). This implies using not only the US GPS system and the European Galileo, but also the Russian GLONASS and the Chinese Beidou. All these systems provide global world coverage, and a platform will be developed within the project (Danube Collaborative Centre) where the observations will be delivered and presented in near-real time. The sensors are being designed by the partners in the GeoNetSee consortium, led by the Faculty of Electrical Engineering of Belgrade University, who are professionals in the field of telecommunications. IGR and other European geological surveys, as partners in the project, will indicate the areas for testing these sensors and provide their geological characterisation.

In this context, we present in this paper three of the five areas proposed to be continuously monitored by the GeoNetSee sensors, thus creating a synergy with the zones surveyed through the GEOMONITOR project and with other zones with known land movements in the Slănic area.

MATERIALS AND METHODS

Old photogrammetric surveys made in Slănic area in the 1970s highlighted zones which suffered continuous land movements in 12-13 years. One such zone is at Băile Verzi, where downwards vertical movements of more than 3 m in the time interval 1968 – 1980 (BULGĂREANU, 1980) were observed nearby the three salt lakes (Fig. 1), together with some smaller areas with upward land movements (and smaller amplitude, maximum value +1.65 m), which could be generated by the material deposited from the nearby landslides.

The second zone is at Baia Baciului and Salt Mountain (Fig. 2), where the photogrammetric surveys (BULGĂREANU, 1984) pointed out 33 areas with downward vertical movements (highest difference of amplitude –23 cm/year) and 9 areas with upward movements (highest difference of amplitude +15 cm/year) in the time interval 1970 – 1983. Although Fig. 1 shows the total vertical movement and Fig. 2 presents the maximum difference of vertical movement/year (or the velocity) observed in the period of 13 years (thus using different types of representation), the order of magnitude of the movement is similar. For Băile Verzi, the maximum vertical movement of -3 m in 12 years would correspond to -25 cm/year in the respective period.

For observing the present trends in land deformations in Slănic area, valuable data are provided by the time series of SAR sensor (Synthetic Aperture Radar), mounted on the Sentinel-1 satellite series launched by the Copernicus programme of the European Space Agency (ESA), to which Romania also takes part through the Romanian Space Agency (ROSA). To facilitate the access of end-users to the processed Sentinel-1 scenes, the Copernicus programme developed the European Ground Motion Service (EGMS), a platform where data for the area of interest can be visualised and downloaded, if needed. EGMS provides radar data processed using the Advanced Differential Interferometry (A-DInSAR) technique (CROSETTO et al., 2020).

Differential Interferometry SAR (DInSAR) is a method of detecting with great accuracy land deformation in the line-of-sight (LOS) of the radar using the phase difference (the interferogram) between pairs of radar images over the same area recorded at different times (DI MARTIRE et al., 2014). Sources of errors in the obtained result can come from atmospheric disturbances and inaccuracies of the Digital Elevation Model (DEM). The Advanced Differential Interferometry SAR (A-DInSAR) overcomes these by using a stack of multiple SAR images acquired during a more extended time period and the derived interferograms. Six processing algorithms were reviewed (MOHAMMED et. al., 2013) and it was found that they all give good results in urban areas but have a poorer performance in suburban and vegetated zones, due to a reduced number of permanent features which could ensure good coherent targets.

Three types of A-DInSAR produts are available on EGMS platform:

- Basic data (level 2A), corrected for the satellite orbit distortion, sensor radiometry, speckle etc. The product is in radar geometry, along the line-of-sight (LOS) of the sensor and is intended for expert usage. It is not possible to compare adjoining satellite frames, even if collected by the same satellite, in ascending or descending orbits.

- Calibrated data (level 2B), where the geometry was corrected based on GNSS points in every satellite frame, so that adjoining areas can be compared. This is considered the main product, meeting the needs of most users.
- Ortho data (level 3) where the ascending (south-north) and descending (north-south) orbit data were combined and two components of movement were obtained: east-west and up-down vertical. Sentinel-1 has a near polar orbit, therefore, it cannot detect land movements along the north-south direction. This product is more straightforward for interpretation.

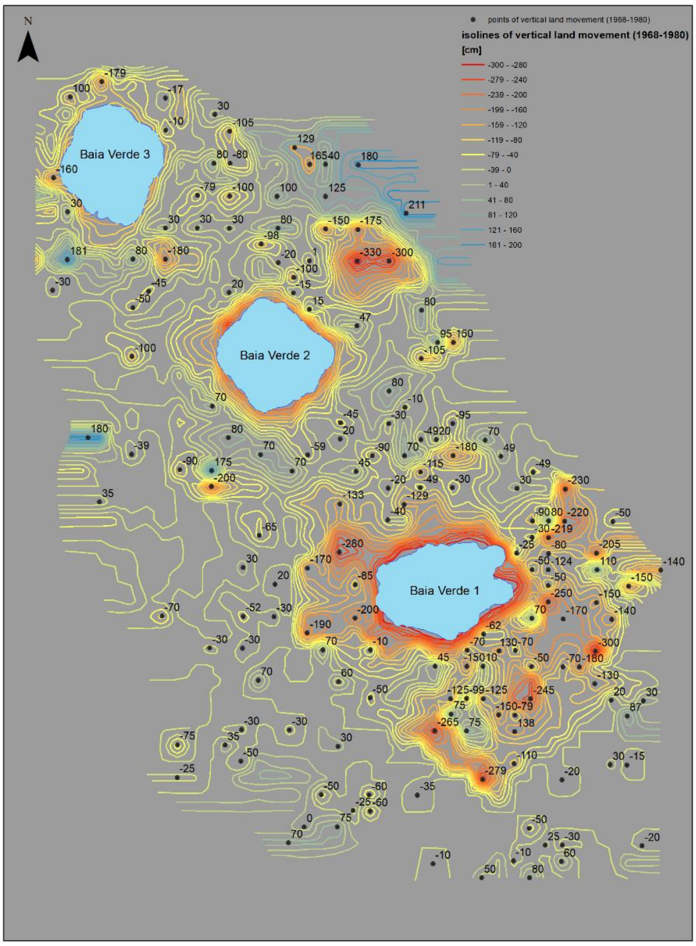


Figure 1. Vertical land movements highlighted by photogrammetric surveys (1968 - 1980) in Băile Verzi area - redrawn and modified after BULGĂREANU (1980).

The EGMS products contain thousands of point-vector data (time series of velocities in mm/year) determined in measurement points (MPs) where the transmitted radar signal backscattered at the sensor was sufficiently strong. The backscatter is influenced by radar parameters (frequency or wavelength and polarisation) and surface parameters (surface roughness relative to wavelength and the moisture content, which influences the dielectric constant). These vector points are colour-coded and each of them contains a time series of millimetre deformation detected at each pass of the Sentinel-1A and 1B satellites (which revisit a place after 6 days), overlaid on a background map or high-resolution image mosaic for orientation purposes.

RESULTS AND DISCUSSION

In this study we used calibrated (level 2B) and ortho (level 3) point-vector maps in the EGMS viewer. Due to journal space constraints, it was not possible to show all the point-vector data for the sites of interest, so the most important ones were selected for exemplification. Fig. 3a shows the point-vector maps (calibrated data) for the central part of Slănic in ascending orbit and Fig 3b in descending orbit. It can be noted that the maps are not identical in terms of colour (velocity of land movement as a yearly average) and localisation of the measurement points (MPs). For the calibrated EGMS product, the point vectors represent the signal recorded in an area of 20 X 5 m. Fig. 3c shows the graph of a MP nearby Baia Baciului and Salt Mt. in satellite ascending mode, highlighting a downward land movement in the area, the elevation difference being at the end of 2023 around -70 mm compared to time t_0 of 2019. The differences in colour for some regions between the point-vector maps in ascending and descending orbits also indicate the existence of an east-west land movement, with some MPs becoming closer to the satellite and others becoming farther away, as shown in the Product User Manual (2022). This was confirmed by the ortho point-vector map for east-west direction, which indicated a movement towards the east, which is normal, as the land masses are going downslope from the western hills to the valley in the east. It is confirmed also by the photogrammetric surveys, which indicated some zones with upwards movements north of the Salt Mt., the effect of deposited geological material transported by landslides, which are frequent in this zone.

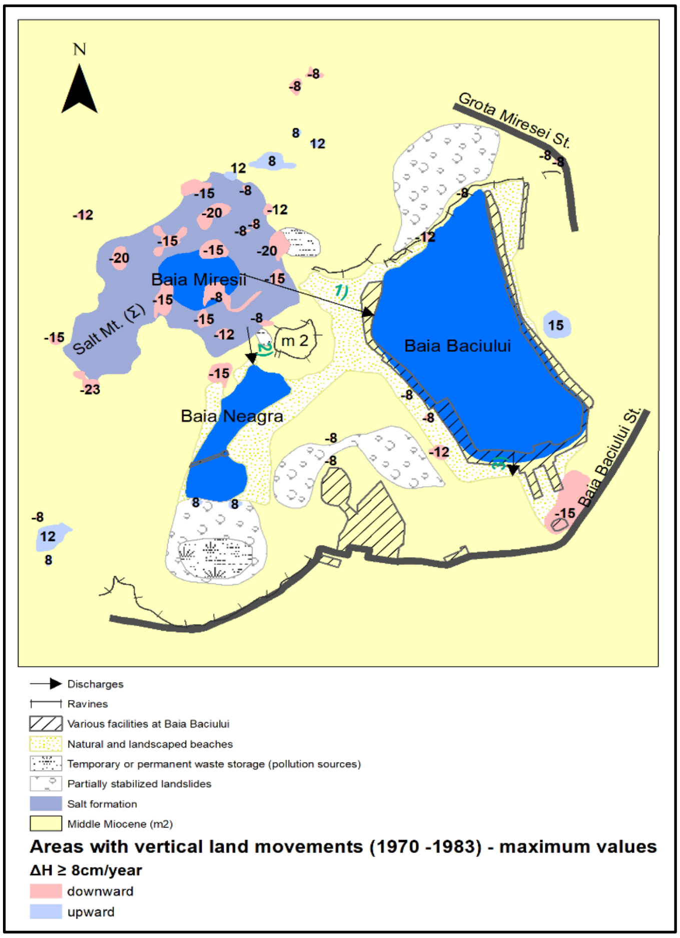


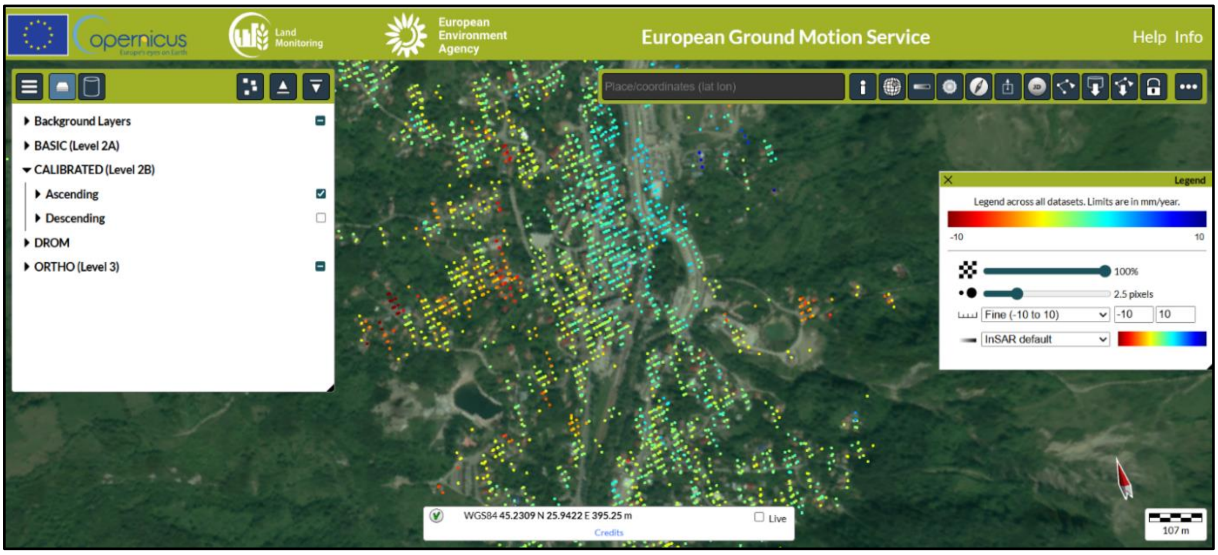
Figure 2. Vertical land movements highlighted by photogrammetric surveys (1970 - 1983)
at Baia Baciului and Salt Mt. - redrawn and modified after BULGĂREANU (1984);
1) Baia Miresii discharge; 2) non-permanent drain; 3) Baia Baciului overflow.

Considering the land deformation data from EGMS (Fig. 3) and archive photogrammetric surveys (Fig. 2), it is proposed that the first land movement monitoring site by GeoNetSee sensors should be near Baia Baciului, in a closed yard where the conditions of safe sensor operation could be fulfilled.

For Băile Verzi the point-vector maps of EGMS ortho product were examined, i.e. the east-west component (Fig. 4a) and up-down vertical component (Fig. 4b). Interrogation at a MP (marked by a green circle) highlighted that in the period January 2019 – December 2023 there was minor deformation on east-west direction (mean velocity 0.4 mm/year, implying stability), while the trend of downward movement was evident, the height difference being over -30 mm in the mentioned period, with a mean velocity of -6.4 mm/year. It is essential to note the difference in MPs distribution in the point-vector maps of the EGMS ortho products, compared to the calibrated product (Fig.3). That is because the EGMS ortho products have been resampled from 20 X 5 m pixel size to 100 X 100 m to make them compatible to other Copernicus products (for example, CORINE Land Cover layer).

Compared to the photogrammetric survey (Fig. 1), the average velocity of downward land movement is lower in radar data (-6.4 mm/year against an estimation of -25 cm/year). Still, the time interval was shorter for radar data (5 instead of 12 years) and it might correspond to a period of more stability in Băile Verzi area. Also, being a rather vegetated zone (pastures, grasslands and deciduous forests), there are few permanent features (roads, roofs of houses) that behave as good radar beam scatterers. This, combined with the decreased ground resolution (resampled 100 m pixel size) can be another cause of reduced average velocity of ground movement in the case of SAR data.

Examining the calibrated EGMS products for a couple of MPs located NE of Baia Verde 1 (see Fig.1), similarly to the MP in Figs. 3a and 3b, the downward trend of the land movement was confirmed on both point-vector maps. The map corresponding to the ascendant orbit showed an average velocity of -6.5 mm/year and the maximum elevation difference around -40 mm, with a high root mean square error RMSE of 4.9 mm, while the map corresponding to the descendant orbit showed average velocities around -12.5 mm/year and maximum elevation difference of -60 mm, with a RMSE of 4.3 mm. The location for the second GNSS sensor will be on one of the properties NE of Baia Verde 1.



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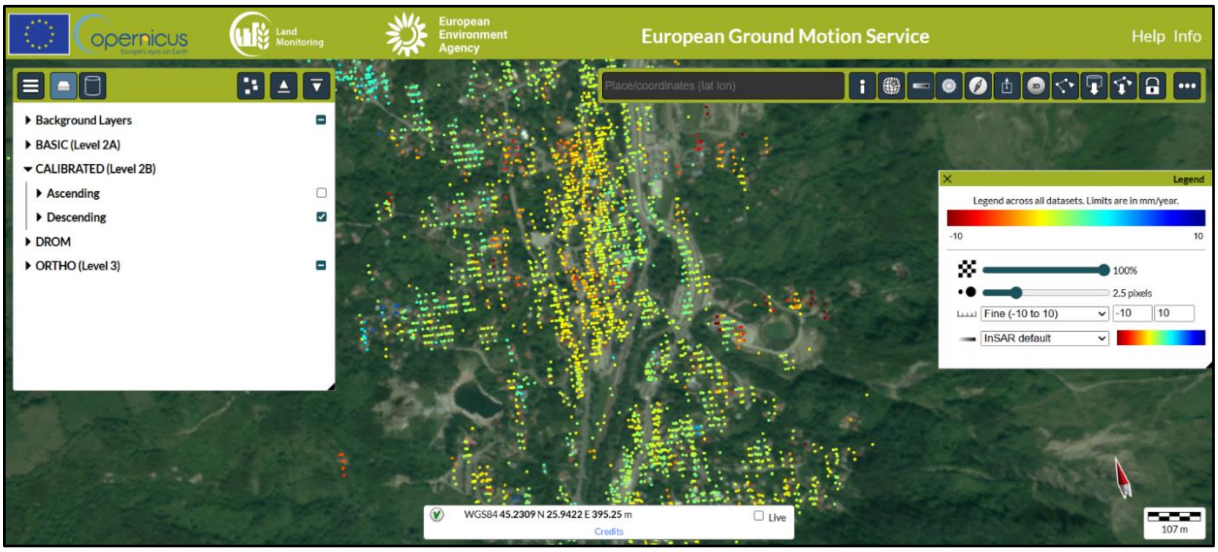
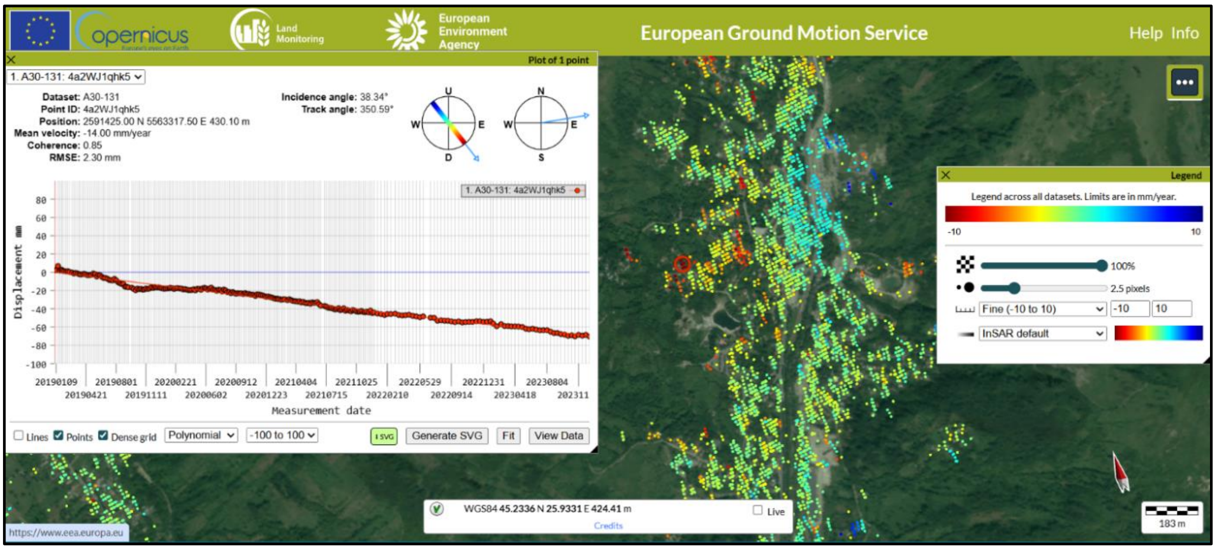
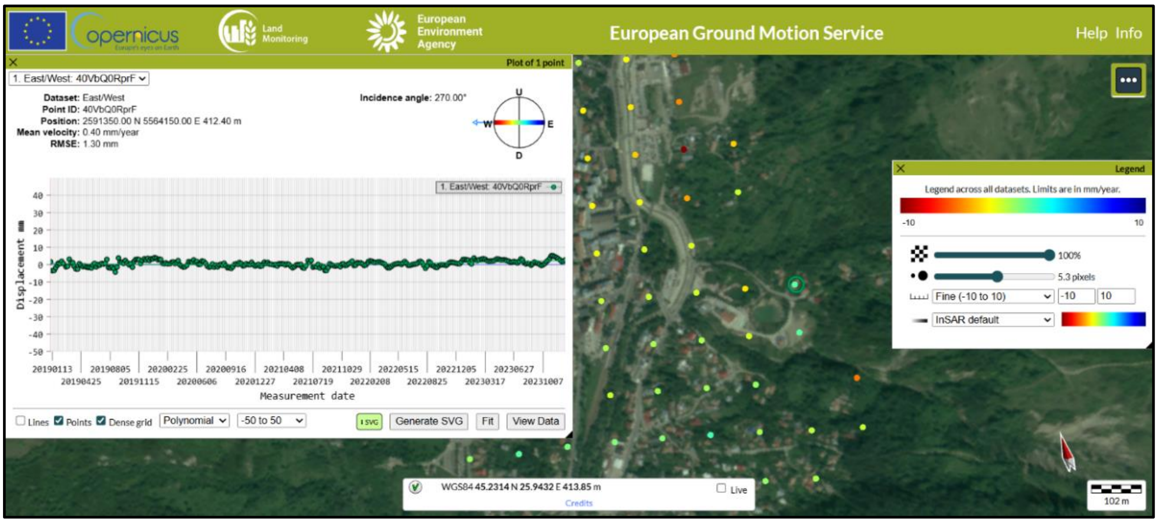


b)

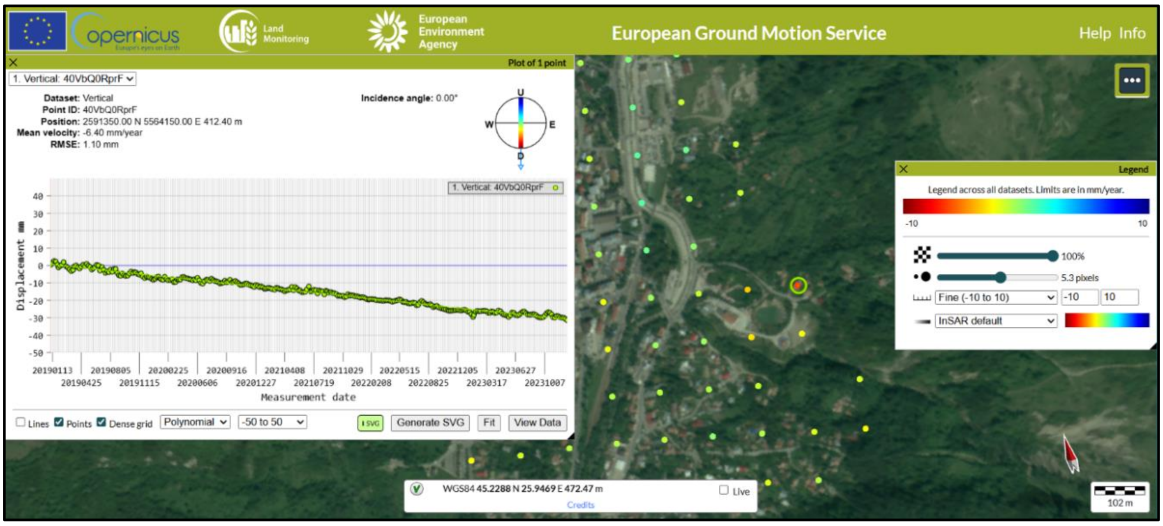


c)

Figure 3. Calibrated SAR point-vector data (2019-2023) in Slănic area; a) ascending orbit; b) descending orbit; c) exemplification of the time-series of land movement (average velocities) for a measurement point (MP) in the vicinity of Baia Baciului and Salt Mt., indicated by a red circle.



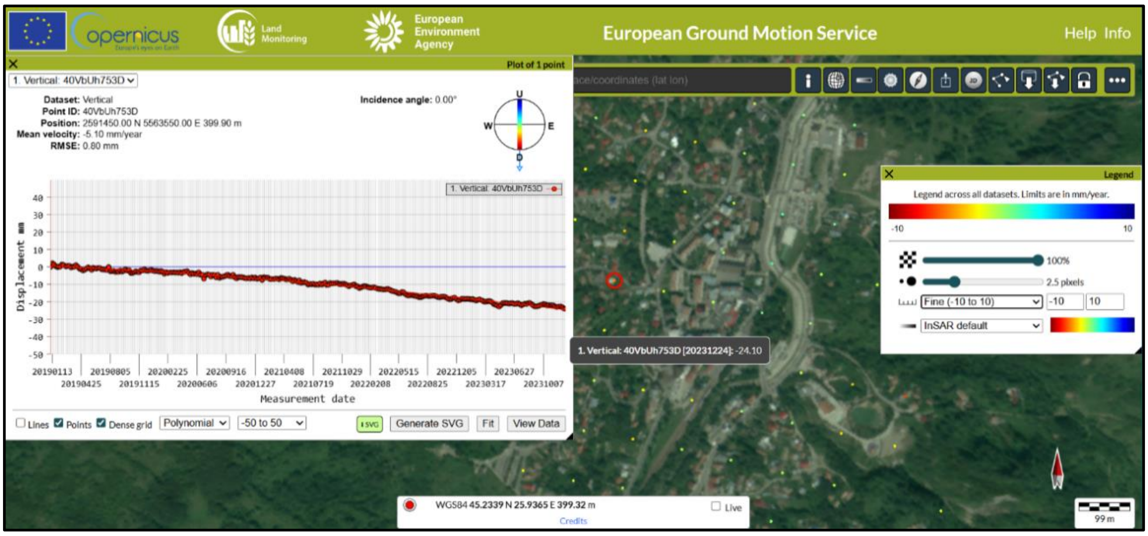
a)



b)

Figure 4. Exemplification of SAR ortho point-vector data (2019-2023) for an MP at Băile Verzi, Slănic, marked with a green circle; a) east-west component, showing little deformation in this horizontal direction; b) up-down vertical component, indicating a progressive downward movement.

The location for the third sensor was established based on field inspections and discussions with the inhabitants, who witnessed periodical formation of a sinkhole on Tudor Vladimirescu St. at number 9, which became afterwards water-filled (Fig 5b left), the water depth being around 60 cm. They used to fill the sinkhole with stones, but after a time, this reappeared. At about 200 m towards SE, there is a place on 23 August St., where in April 2024 the road collapsed, and the nearby blocks of flats were endangered (Fig. 5b-right). The EMGS ortho product highlights on Tudor Vladimirescu St. a downward movement of -5.10 mm/year, with a RMSE of 0.8 mm, the maximum elevation difference being around -24.10 mm for the period 2019-2023 (Fig. 5a). The ortho east-west component shows stability. Both calibrated point-vector maps (ascending orbit and descending orbit) confirm the downward movement, with more red and orange-coded points than the ortho up-down vertical component. It is possible to have the graph for a polygon containing more points and this is exemplified in Fig. 5c, where a polygon (encompassing the mentioned habitation on Tudor Vladimirescu St. and the subsidence-affected portion of 23 August St.) was drawn, including 10 MPs. The graph shows for these 10 points an average downward velocity of -3.19 mm/year for the ortho vertical component, with a RMS of 0.8 mm, the maximum elevation difference being -18.37 mm. This is an essential feature of EGMS, as it is advisable to look for agglomerations of points indicating intense downward or upward movement and not isolated points. For this reason, both EGMS products (calibrated and ortho) should be inspected, as they offer complementary information. Considering the vicinity of these two streets, it appears that the deformations which occurred in these zones have a common geological cause, which has not been identified yet. The GNSS sensor that will be installed (most probably on the mentioned property on Tudor Vladimirescu St.) will hopefully contribute to solving this issue by offering continuous monitoring of the land movements, complementing the ongoing surveys of the GEOMONITOR project.



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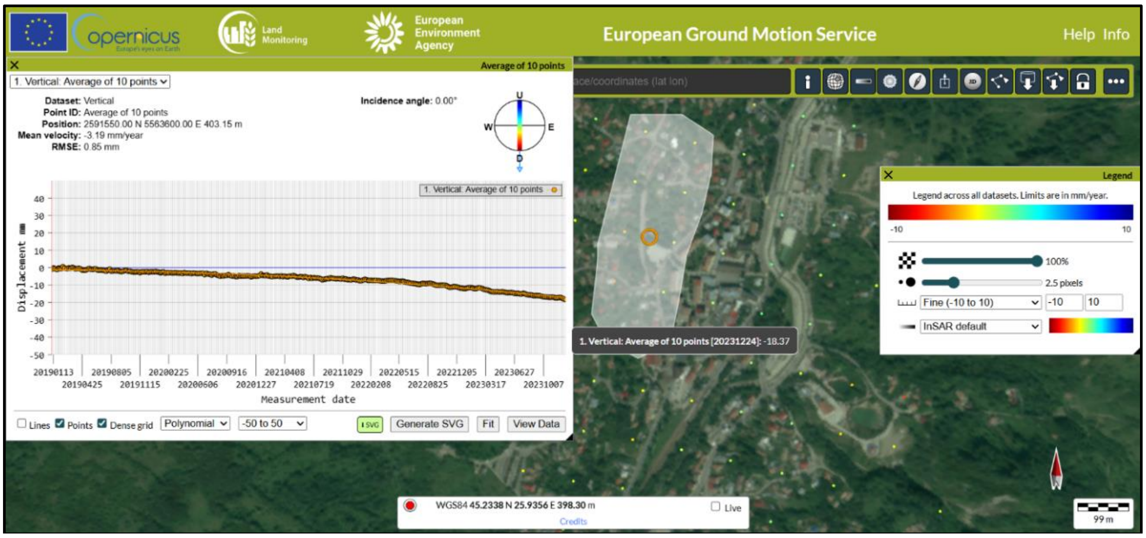

c)

Figure 5. Exemplification of SAR ortho point-vector data for the third selected site in Slănic;
a) progressive downward movement for a MP on Tudor Vladimirescu St.; b) left - the sinkhole on Tudor Vladimirescu St. in April 2025; right - the sinkhole which affected 23 August St. (April 2024); c) progressive downward movement (average for 10 MPs in the polygon which includes the areas shown in part b of the figure.

CONCLUSIONS

Examination of EGMS calibrated and ortho point-vector data showing the direction and velocity of land movements as colour-coded points proved to be very useful for selecting new sites where state-of-the-art GNSS monitoring sensors are to be installed. Combined with available high-resolution deformation data from archives (in this case, photogrammetric surveys dated the 1970s), the radar data confirmed that the trend of land movements continues in areas of Slănic where old bell-shaped salt mines turned into salt lakes (Băile Verzi, Baia Baciului, Baia Miresii). This is not unexpected, but there are other areas without salt outcrops or known exploitations, where land deformations have been reported, their cause is not fully known yet and solutions are still to be found.

For identifying areas with ground instabilities, both calibrated and ortho EGMS data must be used. Firstly, the ortho products are used for understanding the type of land movement, and the calibrated products are used for obtaining greater details over the area of interest. A further step would be downloading the data sets (as CSV files) and using them in a GIS environment. Thus, it will be possible to find other areas with active and intense land deformation and, in combination with auxiliary information, to map the most vulnerable zones.

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