UDC 528.8.044.2

Denys KUKHTAR[1*], Roksolana OLESKIV[2]

[1] Department of Higher geodesy and astronomy, Lviv Polytechnic National University, 12, S. Bandery str., Lviv, 79013, Ukraine, e-mail: kukhtar3088@gmail.com, https://orcid.org/0000-0002-2839-4318

[2] Department of Geodesy and Land Management, Ivano-Frankivsk National Technical University of Oil and Gas, 15, Karpatska str., Ivano-Frankivsk, 76019, Ukraine. https://orcid.org/0000-0003-0334-3028

https://doi.org/10.23939/istcgcap2024.100.033

SURFACE DEFORMATIONS ANALYSIS OF UNDERGROUND GAS STORAGE USING PSINSAR BASED ON SENTINEL-1 SATELLITE DATA

The purpose of this research is to utilize the Persistent Scatterers InSAR method for studying cyclic movements of the Earth's surface caused by technological processes involved in exploiting the underground gas storage facility. The objective of this research is the area of the Bohorodchany underground gas storage facility, which was constructed at a depleted gas reservoir. The research input data were thirty-nine (39) SAR images acquired by the Sentinel-1 satellite in the Interferometric Wide mode from an ascending orbit. The time series covered the period from May 31, 2021, to December 23, 2023. The time interval between the images was 24 days. The SNAP2StaMPS v2.0 algorithm enabled the preliminary preparation of radar images. The introduction of additional functions has significantly improved the operation convenience and reliability. The Stanford Method of Persistent Scatterers (StaMPS) was used to process radar images applying by the Persistent Scatterers technique. This method is implemented in the MatLab program. In the course of the data processing, the influence of atmospheric effects was taken into consideration. TRAIN toolkit was used for this purpose. It calculates the linear tropospheric delay of a radar signal and makes the required corrections. The visualization of deformation velocity maps of the gas storage area was implemented via the StaMPS-Visualizer. It has been established that the PSInSAR method allows to analyzing a time series of deformations in the area of both industrial sites and technological wells. The practical significance of the research results consists in the formulation of recommendations for the effective application of the PSInSAR method as a component of geodetic monitoring at the Bohorodchany underground gas storage facility.

Key words: gas storage facilities, radar interferometry, persistent scatterer, StaMPS, TRAIN.

Introduction

Underground gas storage facilities (UGSF) are rated as strategically important engineering objects that play a key role in ensuring uninterrupted gas supply for industrial and domestic needs. The accumulation and storage in gas facilities effectively manage the seasonal demand for natural gas and provide reserves for unforeseen supply disruptions. This practical experience is used not only in Ukraine but also in European countries.

The three main types of underground gas storage facilities are based on the geological structures they are constructed upon: depleted gas reservoirs, aquifers, and salt caverns. The storage facilities based on depleted gas fields are the most widely spread type, including Ukraine. Their share is approximately 80 % among all gas storage facilities [NaturalGas.org, 2024]. This storage facility type is most effective. It ensures the basic load during operation, which corresponds to seasonal changes in gas consumption by users. Meanwhile, to meet the needs of peak load that corresponds to the moments of rapid gas extraction in large volumes within a short period, gas storage facilities are constructed in aquifers and salt caverns [Tajdu´s et al., 2021].

Periodic natural gas injection and extraction cause pressure changes in a reservoir bed, reaching 2–10 MPa [Teatini et al., 2011]. The variable stresses arise in the geological structure exactly under the impact of operation cyclicity and pressure changes in a wide range. This can lead to the loss of gas storage hermeticity or damage to the equipment, particularly with injection/withdrawal wells. The expected operational lifespan of underground gas storage facilities is several decades. Therefore, constant monitoring of underground storage facilities is crucial to guarantee their safe uninterrupted and reliable operation.

The monitoring of UGSF areas, which have a technogenic impact on the geological and ecological environment, involves a number of geotechnical studies. Geochemical [Znak et al., 2015] and geodetic methods [Perovych and Begin, 2017; Oleskiv, 2017] play an important role in this process. The subject of geodetic monitoring research is the vertical movements of a gas storage roof and their amplitude in the course of gas injection and withdrawal [Dudlia et al., 2012].

To clarify the purpose of a geodetic component of research, we should examine the key geomechanical processes that occur within a gas storage facility and how these processes affect the facility's operational reliability. Specifically, when a gas storage facility is constructed on a depleted field, the roof of the facility shifts to its natural position once it is filled with gas. At the same time, such pressure appears in the reservoir bed, which was before the gas field development, while the stress-strain state of the surface disappears. After gas is extracted from a storage facility, the pressure drops, and the stress-strain state of the surface rises due to the existing roof subsidence. These processes cyclically repeat from year to year, thus leading to periodic vertical movements of the surface above a gas storage facility: uplifting during the gas injection period (April–October) and subsidence during the gas withdrawal period (November–March). The UGSF operates reliably and safely under the plastic nature of gas storage roof deformations, which corresponds to seasonal operation cycles.

Geometric leveling is one of the most reliable geodetic monitoring methods at UGSF. Among the restrictions typical for this method, one should mention the spatiotemporal discreteness of measurements. This means that assessment of vertical movements of the Earth's surface is performed by measuring change in height of benchmarks over a period between observation campaigns, which can last for several months. While monitoring using the GNSS methods enables faster surveying, it also does not guarantee high spatiotemporal resolution in the measurement results as a terrestrial method.

The development of a high-precision three-dimensional deformation field for an underground storage roof can be accomplished through the collaborative use of both terrestrial and remote sensing methods. The satellite radar interferometry results (InSAR) are widely used to solve these problems [Kim et al., 2021; [Liu et al., 2023]. This technology is often applied for geodynamic monitoring of the areas, where oil and gas fields are being developed [Mu'Amalah et al., 2021; Eckles, 2023]. It is also applied in areas with high groundwater consumption, particularly around large urban agglomerations [Vaka et al., 2021], and in the projects involving underground CO_2 storage [Vasco et al., 2022]. A common characteristic of the projects mentioned above is the ability to detect gradual deformations of the Earth's surface with millimeter precision. These deformations occur due to the filling or depletion of underground geological structures. Since the patterns of these deformations resemble those found in gas storage roofs, satellite radar interferometry has proven to be an effective method in geodynamic studies related to underground gas storage facilities (UGSF) [Ferretti et al., 2014; Rapant et al., 2020; Struhár et al., 2022].

Object of research

The objective of this research is the area of the Bohorodchany underground gas storage facility (Ivano-Frankivsk region), which was put into operation in 1979. The Bohorodchany UGSF was constructed in the middle sand-aleurolitic horizon of the South-Eastern block of the area 5.5×3.5 km^2. The internal limit of gas bearing capacity is 7.5×4.5 km^2. The South-Western geological fold is limited by deposits of the Stebnyk thrust, while the North-Western geological fold joins the Hrynivka deposit. From the North-East and West, the gas horizon is limited by tectonic deposits [Oleskiv, 2017].

The previous study on determining the dynamics of a gas storage roof, based on the radar data obtained from the Sentinel-1 satellite, is presented in the article [Kukhtar & Oleskiv, 2023]. The differential interferometry method (DInSAR) was applied in this study. The impact of errors on the results, such as inaccuracies in satellite positioning, digital elevation models (DEMs), and atmospheric effects, is comparable to the magnitude of deformations occurring on the Earth's surface. It is known that the DInSAR method can be effectively employed when deformations are significantly greater than these error values. Therefore, DInSAR does not have sufficient sensitivity to detect seasonal plastic deformations in gas storage facilities. An alternative method must be used.

The purpose of research

This research focuses on the slow and cyclic movements of the Earth's surface above a gas storage facility. To analyze these movements, we will process satellite radar images using advanced differential interferometry techniques, along with multiple time series data. Such methods include the method of Persistent Scatterers (PSI).

The purpose of this research is to utilize the PSI method for studying cyclic movements of the Earth's surface caused by technological processes involved in exploiting the Bohorodchany underground gas storage facility.

Initial data and methods

The Persistent Scatterers InSAR method (PSI) is an advanced technique of interferometric processing of a synthetic aperture radar image (SAR). It helps to highly precisely detect deformations of the Earth's surface and structures by revealing and analyzing the points that remain clearly identifiable over time (the so-called "*persistent scatterers*"). These objects usually have high reflectivity and are not affected by atmospheric or other external factors. When using the data from several radar images obtained at different moments, PSI ensures the highly precise detection of slow surface deformations caused by natural or man-made factors.

The input data for the research were thirty-nine (39) SAR images acquired by the Sentinel-1 satellite from an ascending orbit. The time series covered the period from May 31, 2021, to December 23, 2023. The time interval between the images was 24 days. The radar images, taken for processing, were obtained in the IW mode (Interferometric Wide) with a spatial resolution of 5×14 m/pixel. The images were downloaded from the Alaska Satellite Facility archive (https://search.asf.alaska.edu/).

The processing of SAR data by the persistent scatterer method (PSI) was performed in two stages by applying the following open-source software products:

1. Automated data preparation using the SNAP2StaMPS algorithm.
2. Implementation of the StaMPS method (Stanford Method for Persistent Scatterers) in the MatLab program.

Step 1. The SNAP2StaMPS algorithm enabled the preliminary preparation of radar images. The processing automation by means of Python scripts allows for effective processing of a large amount of initial data. As a result, the subset of the images within the area of interest was created. Applied orbit files for each acquisition were used, the co-registration of master-secondary pairs of images was performed, and the corresponding interferograms were generated.

The SNAP2StaMPS package has now been updated to version 2.0 (https://github.com/mdelgadoblasco/snap2stamps/releases/tag/2.0). The previous version of SNAP2StaMPS v1.0 required a stage to define the master image among the time series via the SNAP program (Sentinel Application Platform). Owing to this update, this stage is no longer needed, as it is performed automatically according to the SNAP2StaMPS algorithm.

The updated version was created based on user requests that were constantly processed after the initial version appeared. In addition to the aforementioned option of automatic selection of the master image, the updated version supports the pre-processing of high-resolution radar data obtained by TerraSAR/TanDEM-X satellites in Stripmap mode (resolution 3×3 m). The TSX2Stamps algorithm of preparing TerraSAR/TanDEM-X data for processing by the PSI method uses the same workflow, as that for Sentinel-1 TOPSAR data. The TSX2Stamps package is also freely available as a separate package for downloading on GitHub (https://github.com/jziemer1996/TSX2StaMPS).

Fig. 1 shows a flowchart of the SNAP2 StaMPS v2.0 algorithm. Here we can see that the updated version of SNAP2StaMPS v2.0, in addition to a new set of commands for preparing TerraSAR/TanDEM-X data, provides a number of optional functions. The introduction of additional functions has significantly improved the convenience and reliability of operation. The *Auto-Download* function ensures the convenience of downloading the data directly from the active archive center of the Alaska Satellite Facility. The advantages of the *Auto-Master Selection* function have already been mentioned above. It is known that after the interferograms were created, each of them must be reviewed and checked for errors. The added function of *Plotting Results* allows forming a folder with the images of all interferograms.

Reviewing them is a quick convenient way to check the quality of the previous stages.

The list below shows the additional features of the updated version of SNAP2StaMPS v2.0 [Delgado Blasco et al., 2023]:

- use of updated versions of Python 3.11 and SNAP v9.0;
- autorun script for full automation of all processing stages;
- the ability to work with two subswath (in case of location of the studied area within separate IW subswath);
- support for various formats for the area of interest definition (BBOX, WKT, SHP, KML, GeoJSON);
- support for an external digital elevation model (SRTM 1 sec is used by default);
- new parameters to optimize the disk space.

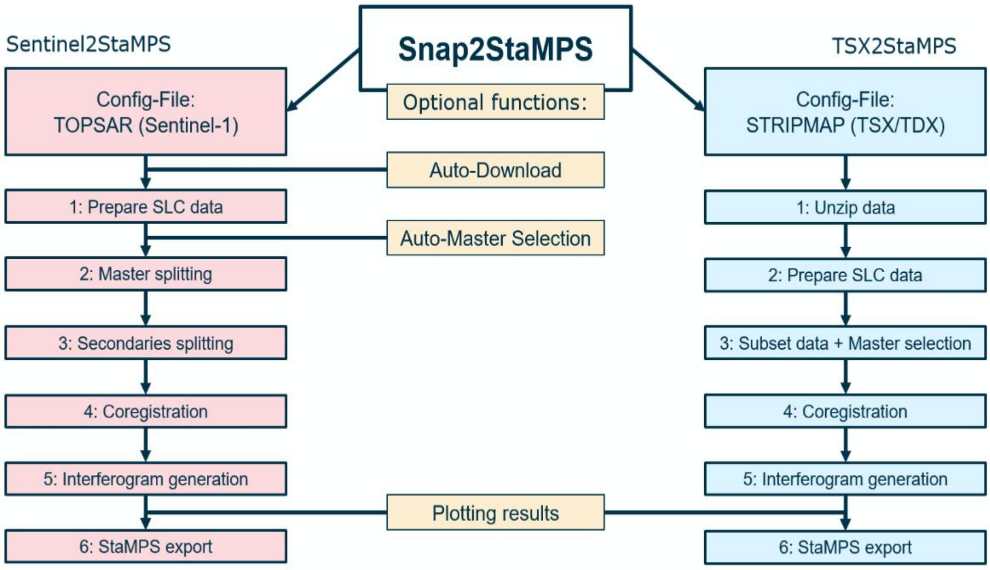

Fig. 1. The flowchart of the automated SAR data preparation process using the SNAP2StaMPS v2.0 algorithm [Delgado Blasco et al., 2023]

Step 2. The Stanford Method of Persistent Scatterers (StaMPS) [Hooper et al., 2012] is a tool for processing radar images, which allows for the detecting of the Earth's surface deformations by using the stable ground points that consistently reflect a radar signal over a long period. This method is implemented in the MatLab program. The data are processed through the MatLab scripts, which identify coherent pixels and single out a component of the signal corresponding to the deformation of the Earth's surface within the range of these pixels. The given algorithm involves seven steps.

One of the advantages of the Persistent Scatterer method is the possibility to exclude atmospheric effects in the interferometric analysis. The Stanford method of persistent scatterers is supported by the TRAIN toolbox, i. e The Toolbox for Reducing Atmospheric InSAR Noise. It is an open-source software product used to reduce the impact of atmospheric effects on InSAR results [Bekaert et al., 2015]. The atmospheric correction can be calculated after the seven steps of the StaMPS algorithm are completed. After that, it is recommended to repeat steps 6 and 7 of the StaMPS algorithm to account for atmospheric and spatially correlated errors in phase unwrapping.

Results

Referring to the results of processing the thirty-nine (39) radar images of the Sentinel-1 satellite by the PSI method, the time series of the Earth’s surface deformations was obtained for the Bohorodchany UGSF site. This research covers 2.5 year period, which corresponds to several periodic cycles of gas storage facility operation.

Fig. 2 shows a map of mean deformation velocities, including the gas storage facility area. The Sentinel-1 satellite is equipped with a right-side radar surveying not at a nadir, but at an angle. Considering this, along with the fact that the images were taken for analysis from an ascending orbit, the resulting velocities were obtained along the satellite's line of sight. In addition, Fig. 2 shows the distribution of the standard deviation value, which sets the quality of defining the deformation velocities. This value does not exceed 1 mm/year for the area of the object studied.

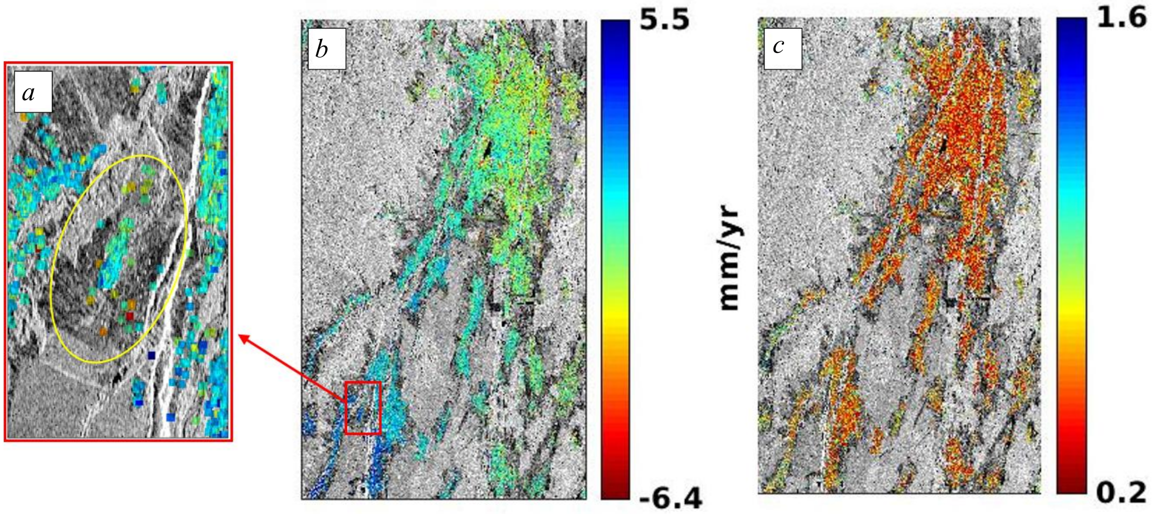

Fig. 2. Mean line-of-sight (LOS) velocity map (31.05.2021-23.12.2023): a – territory of underground gas storage in Bohorodchany (approximate boundary), b – the processed territory within SAR images; c – standard deviation of mean LOS velocities

During the data processing by the Persistent Scatterers method, certain corrections were taken into consideration for spatially correlated errors, such as those from the digital elevation model and orbital errors, as well as the influence of atmospheric effects. First of all, the TRAIN toolkit was used for this, it calculates the linear tropospheric delay of a radar signal and makes the required corrections [Kukhtar, 2024]. Fig. 3 shows the distribution of tropospheric delay of a radar signal caused by the atmospheric impact at the moment of acquisition. Such a generalized picture helps to estimate the phase impact of the atmosphere on each of the images and, if necessary, to delete such an image from the processing chain.

After calculating the tropospheric signal delay, the steps 6 and 7 of the StaMPS algorithm are repeatedly executed to jointly estimate the spatially correlated and atmospheric corrections during the phase unwrapping process.

To verify the effectiveness of the corrections used, the MatLab program environment was utilized for sequential visualization of mean velocity maps (Fig. 4). In this case, the range of mean deformation velocities of the investigated area changes to some extent. This is common, when the magnitude of values practically does not change after involving the above corrections, while the upper and lower limits of the range decrease proportionally.

The presentation of data in MatLab is not always convenient and visually understandable. Therefore, the StaMPS algorithm provides the possibility to visualize the maps of mean deformation velocities on an optical satellite image. To do this, the set of obtained data is exported in *.kmz file format for visualization in GoogleEarth. The StaMPS-Visualizer application is another method [Höser, 2018]. This program is publicly available and allows not only visualizing the data on an optical satellite image, but also analyzing the time series of deformations for each persistent scatterer and present the data in the form of graphs.

Fig. 5 presents a map of deformations of the Earth's surface velocities along the satellite's line of sight to the Bohorodchany gas storage area, created using StaMPS-Visualizer.

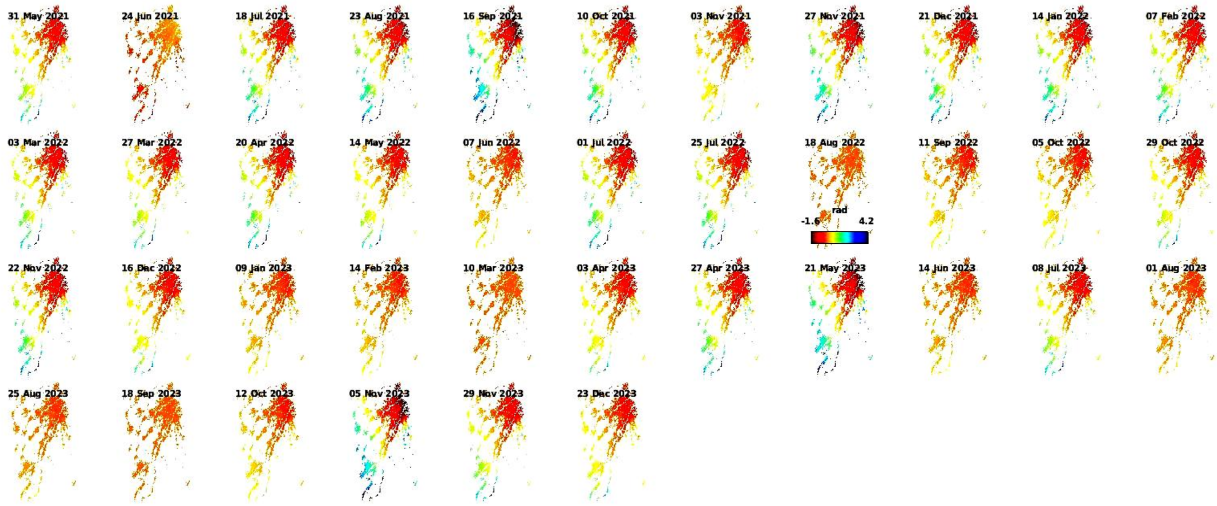

Fig. 3. Tropospheric signal delay for the investigated territory during 31.05.2021–23.12.2023, rad

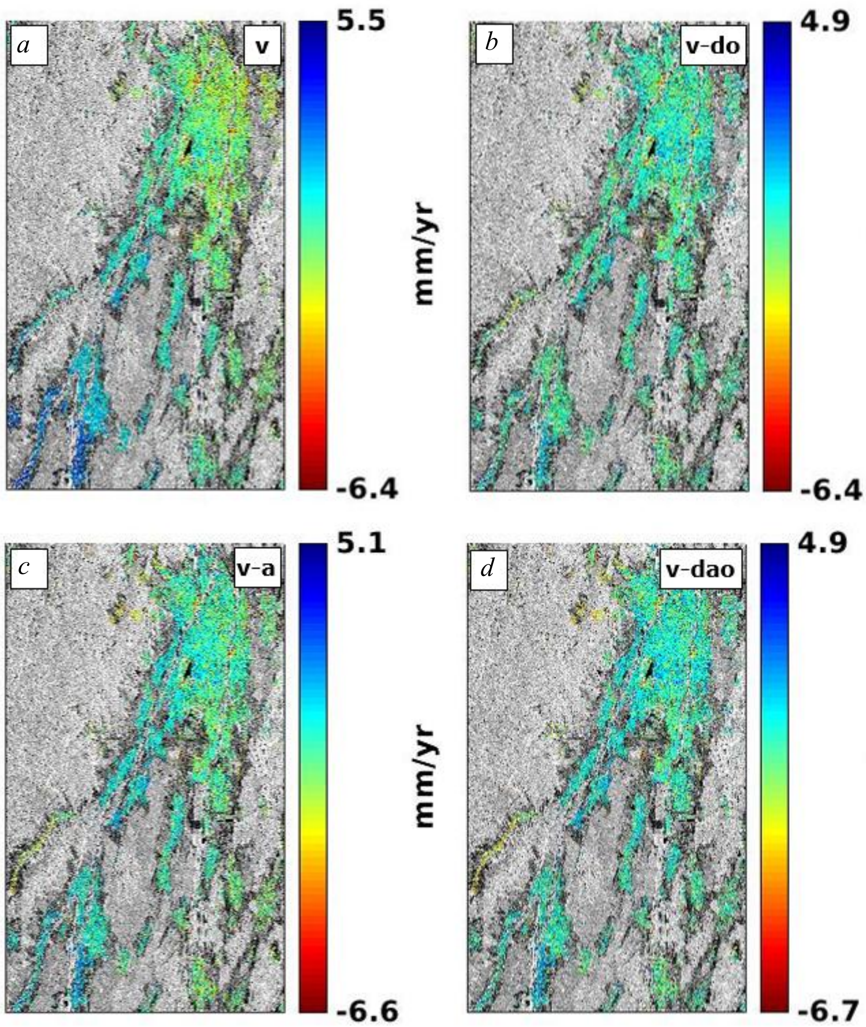

Fig. 4. Mean line-of-sight velocity maps of the investigated area: a – velocity map without any corrections (v); b – velocity map with DEM corrections and orbit ramps corrections (v-do); c – velocity map with tropospheric corrections (v-a); d – velocity map with DEM corrections , tropospheric and orbit ramp corrections (v-dao)

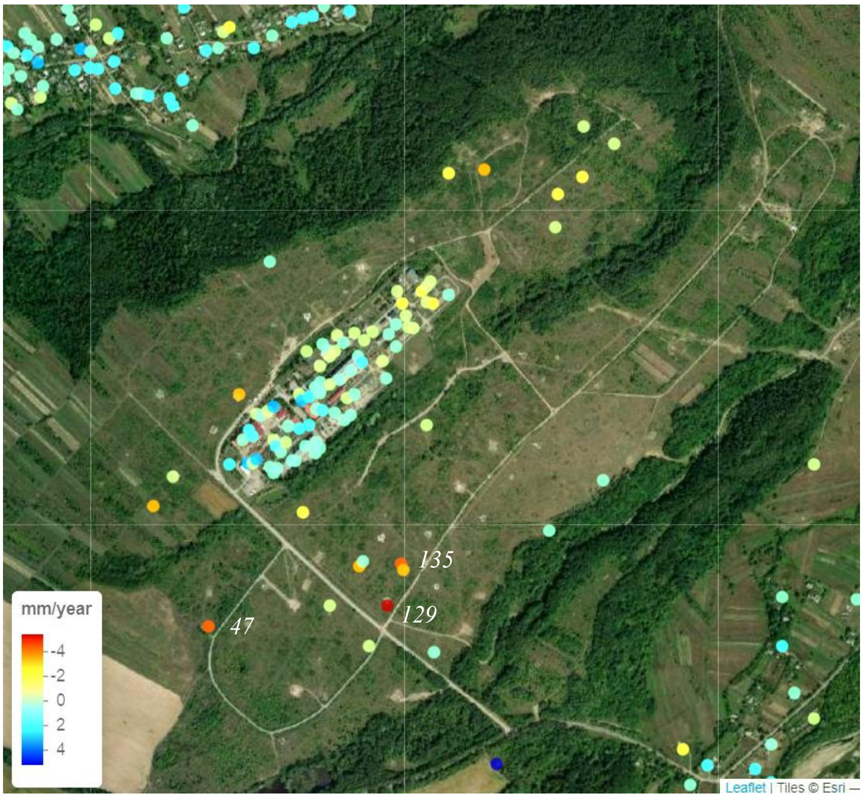

Fig. 5. Mean LOS velocity map of the territory of underground gas storage in Bohorodchany obtained by the PSInSAR method (31.05.2021–23.12.2023)

Persistent scatterers are mainly concentrated on the sites of structures and artificial objects. In particular, they are located in the area of technological equipment and administrative buildings. The analysis of the time series of deformations demonstrates the general stability of the industrial site. The mean deformation velocities are close to zero on the site of technological equipment.

Persistent scatterers on technological wells provide the most important information for geodetic monitoring. Such wells are clearly distinguished in radar images due to the high amplitude of the signal reflected. Nevertheless, Fig. 5 makes it clear that only some parts of technological wells, scattered in the gas storage area, are identified as persistent scatterers. The rest of them are weeded out (excluded) during processing due to decorrelation. Decorrelation increases due to loss of signal coherence between two or more images used in interferometric analysis.

We believe that the nature of decorrelation on this site is related to seasonal changes occurring in the environment (vegetation structure, snow cover). The basic approach to overcome the impact of seasonal surface changes, when using the satellite radar interferometry, is the involvement of ground-based corner reflectors [Aguado et al., 2015]. Therefore, we recommend deploying a network of corner reflectors on/near the technological wells for geodetic monitoring of a gas storage area by the satellite radar methods.

As shown by the analysis of the time series of deformations on wells, the vast majority have a stable position during the whole research period. The time series of data may be burdened by noise components, which were not deleted during processing in this case (Fig. 6). In connection with this, it is necessary to consider the averaged data in the deformation analysis.

Some persistent scatterers of wells indicate the tendency to subsidence and non-plastic deformations. Fig. 7 presents the deformation graphs of three points (see Fig. 5: No. 47, No. 129, No. 135), characterized by the highest subsidence rate over the period studied.

To correctly interpret the data, further analysis of geodynamic processes, occurring in the area of a gas storage facility, must be carried out, provided that there is technological process data on gas injection/withdrawal during exploitation. Moreover, the results of satellite radar monitoring require additional verification using the data from ground-based geodetic observations (e. g. geometric or GNSS-leveling).

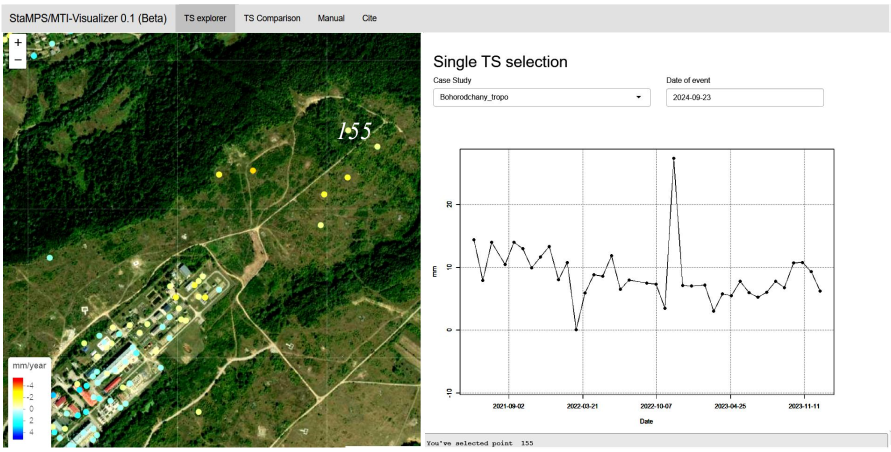

Fig. 6. Time series of the permanent scatterer №155 deformation at the technological well

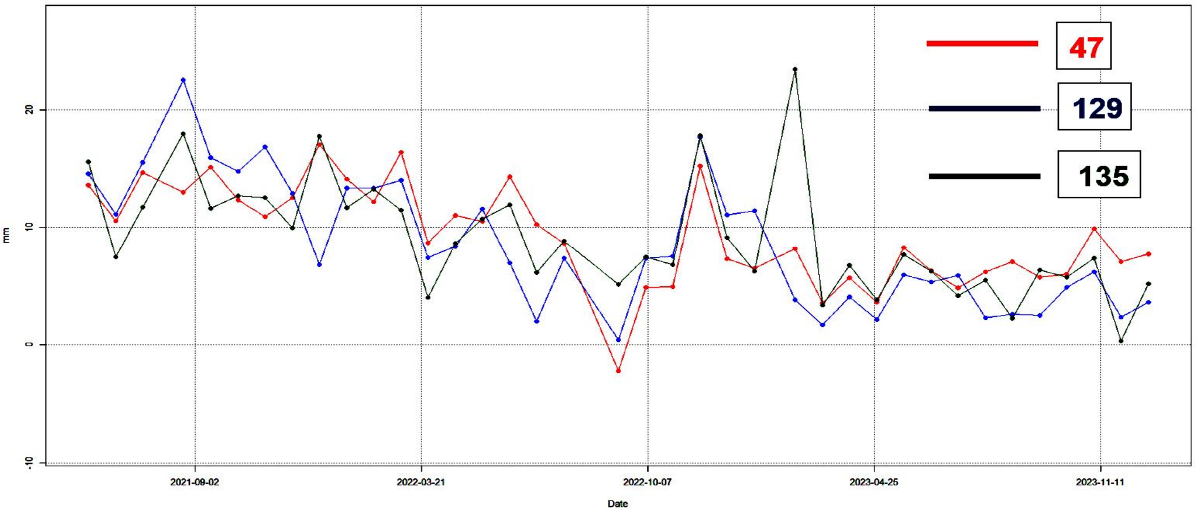

Fig. 7. LOS deformation time series of the permanent scatterers No. 47, No. 129, No. 135 at the technological wells

Scientific novelty and practical significance

The results of satellite radar monitoring were obtained on the Bohorodchany UGSF site for 2.5 years of the gas storage facility operation. It has been established that the PSInSAR method allows the analysis of a time series of deformations on the area of both industrial sites and technological wells.

The practical significance of the research results consists in the formulation of recommendations for the effective application of the PSInSAR method as a component of geodetic monitoring at the Bohorodchany UGSF. The core recommendation is the deployment of a network of ground-based corner reflectors to improve signal coherence on radar images.

Conclusions

The use of the satellite radar interferometry method, as illustrated in the Bohorodchany UGSF area, shows its efficiency and cost-effectiveness for monitoring the underground gas storage facilities based on the remote sensing data. When combined with land surveying techniques, such as geometric leveling and GNSS observations, the InSAR method can provide valuable insights into the spatiotemporal distribution of deformations in the roof of the underground gas storage.

All production wells shall be equipped with ground-based corner reflectors to ensure the reliability of deformation detection results. This will enable getting a high constant value of reflected radar signal and reducing the decorrelation impact when processing the long time series of radar data.

Thanks to the open access to radar data, which are constantly collected and updated every 12 days, the use of radar interferometry for monitoring underground gas storage facilities can provide a solid foundation for an early warning system that detects critical deformations at these sites. This system will enhance the operational reliability of underground gas storage facilities by enabling timely responses to potential issues.

References

Aguado, V., Vink, A., James, B., Biescas, E. (2015). An improved combination of Natural Reflectors and Corner Reflectors to monitor surface heave generated by SAGD operations using InSAR satellite technology. *World Heavy Oil Congress 2015.* Edmonton, AB, Canada. Volume: WHOC15-321.

Bekaert, D. P. S., Walters, R. J., Wright, T. J., Hooper, A. J., and Parker, D. J. (2015). Statistical comparison of InSAR tropospheric correction techniques. *Remote Sensing of Environment*. https://doi.org/ 10.1016/|j.rse.2015.08.035

Delgado Blasco, J. M., Ziemer, J., Foumelis, M., & Dubois, C. (2023). SNAP2StaMPS v2: Increasing Features and Supported Sensors in the Open Source SNAP2StaMPS Processing Scheme (2.0). FRINGE Workshop 2023, Leeds, UK. Zenodo. https://doi.org/ 10.5281/ zenodo.8362628

Dudlia, M. A., Shirin, L. N., & Fedorenko, E. A. (2012). Processes Of Underground Gas Storage. *Course book.* Dnipropetrovsk, NMU. 412 p. ISBN 978-966-350-364-6 *(in Ukrainian).* https://core.ac.uk/download/ pdf/48402493.pdf

Eckles, E. (2023). Oilfield Ground Displacement Monitoring Using SAR Data. Retrieved December 1, 2024, https://www.nv5geospatialsoftware.com/ Learn/Case-Studies/Case-Studies-Detail/ArtMID/10204/ArticleID/24281/Oilfield-Ground-Displacement-Monitoring-Using-SAR-Data

Ferretti, A., Rucci, A., Tamburini, A., Del Conte, S. and Cespa, S. (2014). Advanced InSAR for Reservoir Geomechanical Analysis. *Conference Proceedings, EAGE Workshop on Geomechanics in the Oil and Gas Industry, May 2014.* https://doi.org/ 10.3997/2214-4609.20140459.

Hooper, A., Bekaert, D., Spaans, K., & Arikan, M. (2012). Recent advances in SAR interferometry time series analysis for measuring crustal deformation. *Tectonophysics*, 514–517, 1–13. https://doi.org/ 10.1016/j.tecto.2011.10.013.

Höser, Thorsten (2018). Analysing Capabilities and Limitations of InSAR Using Sentinel-1 Data for Landslide Detection and Monitoring. Master's thesis, Bonn: Department of Geography, Bonn University

Kim, T. T. H., Tran, H. H., Bui, K. L., & Lipecki, T. (2021). Mining-induced Land Subsidence Detected by Sentinel-1 SAR Images: An Example from the Historical Tadeusz Kościuszko Salt Mine at Wapno, Greater Poland Voivodeship, Poland. *Inżynieria Mineralna*, *1*(2). https://doi.org/10.29227/IM-2021-02-04

Kukhtar, D. (2024). A Method of Tropospheric Signal Delay Correction in Satellite SAR. *Modern Achievements of Geodetic Science and Industry*. No. 2 (48), 41–48. https://doi.org/10.33841/1819-1339-2-48-41-48 *(in Ukrainian).*

Kukhtar, D. & Oleskiv, R. (2023). Differential radar interferometry method for monitoring the areas of underground gas storage station. *Technical Sciences and Technology*, 3 (33), 235–241. https://doi.org/ 10.25140/2411-5363-2023-3(33)-235-241 *(in Ukrainian).*

Liu, C., Ji, L., Zhu, L., Xu, C., Zhang,W., Qiu, J., & Xiong, G. (2023). Present-Day Three-Dimensional Deformation across the Ordos Block, China, Derived from InSAR, GPS, and Leveling Observations. *Remote Sensing*, 15, 2890. https://doi.org/ 10.3390/rs15112890

Mu'Amalah, A., Anjasmara, I. M., & Taufik, M. (2021). Land Subsidence Monitoring in Cepu Block Area Using PS-Insar Technique. *IOP Conference Series: Earth and Environmental Science,* 731(1), Article 012011. https://doi.org/10.1088/1755-1315/731/1/012011

NaturalGas.org (2024, December 1). *Storage of Natural Gas*. http://naturalgas.org/naturalgas/ storage/

Oleskiv, R. Ye. (2017). Investigation of stress-strain state of underground gas storage wells based on geodetic measurement. *Dissertation on acquisition of PhD scientific degree by specialty 05.24.01.* Kyiv National University of Construction and Arhitecture. MSE of Ukraine, Kyiv.

Perovych, L., & Begin, S. (2017). Seasonal deformation processes at under groundgas storage station. *Baltic surveying. International scientific journal.* Volume 6. 83-86. https://llufb.llu.lv/Raksti/Journal_Baltic_Surveying/2017/Journal_Baltic_SurveyingVol6_2017-83-86.pdf

Rapant, P., Struhár, J., & Lazecký, M. (2020). Radar Interferometry as a Comprehensive Tool for Monitoring the Fault Activity in the Vicinity of Underground Gas Storage Facilities. *Remote Sensing,* 12. 271. https://doi.org/10.3390/ rs12020271

Struhár, J.; Rapant, P.; Kaˇcmaˇrík, M.; Hlaváˇcová, I.; & Lazecký, M. (2022). Monitoring Non-Linear Ground Motion above Underground Gas Storage Using GNSS and PSInSAR Based on Sentinel-1 Data. *Remote Sensing,* 14. 4898. https://doi.org/ 10.3390/rs14194898

Tajdu´s, K., Sroka, A., Misa, R., Tajdu´s, A., & Meyer, S. (2021). Surface Deformations Caused by the Convergence of Large Underground Gas Storage Facilities. *Energies,* 14, 402. https://doi.org/ 10.3390/en14020402

Teatini, P., Castelletto, N., Ferronato, M., Gambolati, G., Janna, C., Cairo, E., Marzorati, D., Colombo, D., Ferretti, A., Bagliani, A. et al. (2011). Geomechanical response to seasonal gas storage in depleted reservoirs: A case study in the Po River basin, Italy. *J. Geophys. Res. Space Phys.* 2011, 116, 21. https://doi.org/10.1029/ 2010JF001793

Vaka, D., Rao, Y., Ojha, C., & Kumar, V. (2021). Mapping land subsidence in Mumbai by Sentinel-1 InSAR time-series. *Fringe 2021.*

Vasco, D., Ferretti, A., Rucci, A., Falorni, G., Samsonov, S., White, D., & Czarnogorska, M. (2022). Geodetic Monitoring of the Geological Storage of Greenhouse Gas Emissions. *Book Series: Geophysical Monograph Series.* https://doi.org/ 10.1002/9781119156871.ch2

Znak, M. S., Lopushnyak, Ya. I., Morhulets, I. M. (2015). Novi tekhnolohii hazoheokhimichnykh doslidzhen dlia kontroliu hermetychnosti pidzemnykh skhovyshch hazu ta okhorony dovkillia. *Rozvidka ta rozrobka naftovykh i hazovykh rodovyshch*. No. 2, 95–102 *(in Ukrainian)*.

Денис КУХТАР[1*], Роксолана ОЛЕСЬКІВ[2]

[1] Кафедра вищої геодезії та астрономії, Національний університет “Львівська політехніка”, вул. С. Бандери, 12, Львів, 79013, Україна, ел. пошта: kukhtar3088@gmail.com

[2] Кафедра геодезії та землеустрою, Івано-Франківський національний технічний університет нафти і газу, вул. Карпатська, 15, Івано-Франківськ, 76019, Україна

АНАЛІЗ ДЕФОРМАЦІЙ ПОВЕРХНІ ПІДЗЕМНОГО СХОВИЩА ГАЗУ МЕТОДОМ PSInSAR НА ОСНОВІ ДАНИХ СУПУТНИКА SENTINEL-1

Мета цього дослідження – застосування методу постійних розсіювачів InSAR для вивчення циклічних рухів земної поверхні, спричинених технологічними процесами експлуатації підземного сховища газу. Об’єктом цього дослідження є територія Богородчанського підземного сховища газу, створеного на місці виснаженого газового родовища. Вхідними даними для досліджень були 39 радіолокаційних знімків, отримані супутником Sentinel-1 із висхідної орбіти у режимі знімання IW (Interferometric Wide). Часовий ряд охопив період з 31 травня 2021 р. до 23 грудня 2023 р. Інтервал часу між зніманнями – 24 дні. Попередню підготовку радіолокаційних знімків виконано за допомогою алгоритму SNAP2StaMPS v2.0. Оновлена версія має кілька додаткових особливостей, які істотно підвищили ефективність застосування набору інструментів. Стенфордський метод постійних розсіювачів (StaMPS) використано для оброблення інтерферометричних радарних зображень методом постійних розсіювачів. Реалізація методу PSI виконана у програмі MatLab. Під час опрацювання даних методом постійних розсіювачів враховано поправки за атмосферні впливи. Для цього використано набір інструментів TRAIN, який виконує розрахунок лінійної тропосферної затримки радіолокаційного сигналу та вводить необхідні поправки. Візуалізацію карт середніх швидкостей деформацій здійснено за допомогою застосунку StaMPS-Visualizer. Встановлено, що використання методу PSInSAR дає змогу виконувати аналіз часових серій деформацій території як промислового майданчика, так і технологічних свердловин. Практичне значення результатів дослідження полягає у формуванні рекомендацій стосовно ефективного використання методу PSInSAR як складової геодезичного моніторингу на Богородчанському газосховищі.

Ключові слова: газосховище, радіолокаційна інтерферометрія, постійний розсіювач, StaMPS, TRAIN.

Received 05.09.2024