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Research paper

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Comprehensive study of anthropogenically unstable territory around the Rivne NPP, Ukraine

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Summary

The article presents an extensive and multifaceted study of the territory surrounding the Rivne Nuclear Power Plant, which were carried out through the integrated use of Earth remote sensing data and advanced geoinformation technologies. The research framework encompasses three interrelated components that collectively provide a holistic understanding of the region's geodynamic and environmental conditions. The first component focuses on identifying and analyzing areas characterized by significant anthropogenic pressure, including zones affected by industrial activity, urban development, and natural landscape transformations. This assessment is supported by high-resolution satellite imagery, which enables the detection of subtle surface changes and land-use dynamics. The second component involves the development of a detailed geoinformation system (GIS) for the Varash municipal territorial community. Using very-high-resolution satellite data, the authors created a multilayer digital model that integrates spatial, environmental, infrastructural, and socio-economic information. This GIS platform supports long-term monitoring, spatial planning, and decision-making at both municipal and regional levels. The third component employs Sentinel-1 interferometric synthetic aperture radar (InSAR) data to determine vertical ground displacements with high precision. The interferometric analysis revealed that vertical deformations across the study area during 2022–2025 ranged from 12 to 30 mm, which indicates the overall stabile ground conditions of the territory around the Rivne NPP. The study highlights the significant potential of modern satellite-based technologies for monitoring critical infrastructure, managing territorial development, and enhancing environmental safety.

Keywords

Earth remote sensing • satellite imagery • interferometry • geoinformation systems • vertical displacements • Rivne NPP

1. Introduction

Remote sensing (RS) occupies a leading position among modern geospatial analysis methods, providing highly effective tools for environmental monitoring, mapping, infrastructure assessment, and the analysis of emergency consequences. Owing to their large spatial coverage, rapid data acquisition, and the availability of multispectral and radar observations, satellite images are widely used in land cadastre, ecology, geodynamics, urban studies, and natural resource management.

The use of RS data is particularly important for assessing the condition of territories exposed to intensive anthropogenic impact or containing objects of increased technological risk. The Rivne Nuclear Power Plant and its surrounding areas represent such zones, where spatial monitoring, infrastructure analysis, and the control of ground-surface deformations are crucial for environmental and technological safety [Davydiuk et al. 2023, Klymenko et al. 2022, Kuznietsov and Biedunkova 2023, Logvinov et al. 2020].

This study provides a comprehensive analysis of the Varash municipal territorial community using satellite data of various types. The main research tasks include:

- development of a geoinformation system of the territory based on very-high-resolution satellite imagery;
- vectorization of major natural and anthropogenic objects;
- creation of a specialized layer of a geodynamic polygon around the Rivne NPP;
- determination of vertical ground displacements using Sentinel-1 interferometry.

Combining optical and radar satellite technologies enabled the formation of a detailed spatial database and the acquisition of quantitative estimates of ground-surface deformations. This paves the way for effective territorial monitoring, informed decision-making, and enhanced environmental safety in the region.

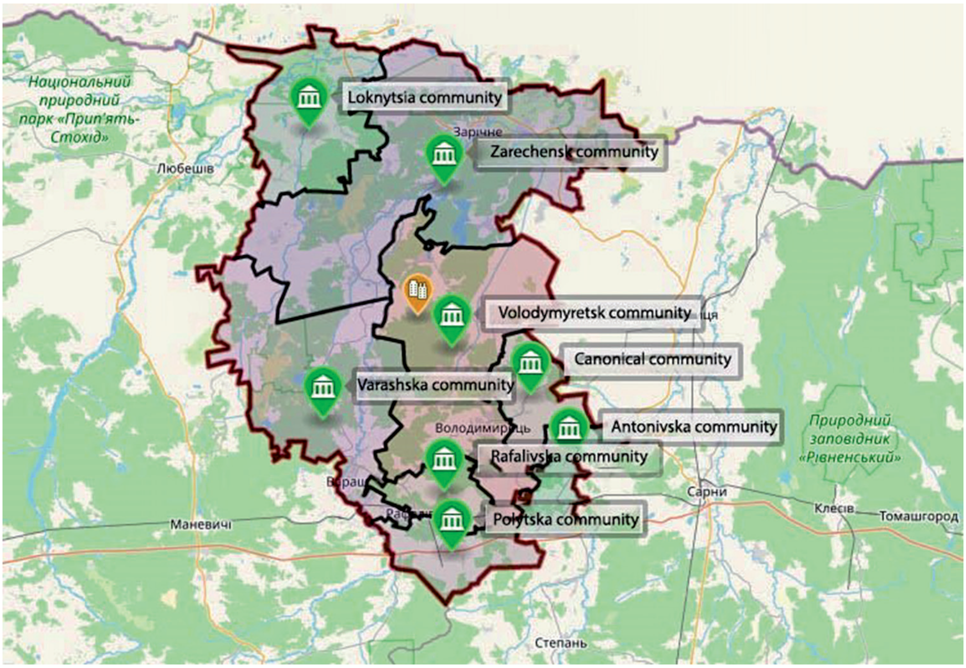
Monitoring of territories that are unstable due to human activity, particularly around nuclear power plants, is currently conducted using satellite interferometry (InSAR), GNSS, and comprehensive geodynamic methods [Dobrokhodova et al. 2025]. InSAR has proven effective for assessing vertical deformations both in naturally active regions and in industrial or anthropogenically loaded areas [Uhlytskykh et al. 2023, Kukhtar 2024]. The use of PSInSAR or multi-temporal approaches is especially valuable as it reduces noise, compensates for atmospheric effects, and allows accurate subsidence or displacement maps to be generated [Tretyak and Kukhtar 2023].

Additionally, the integration of GIS thematic layers, satellite data, and ground observations provides an assessment of deformations in the context of anthropogenic loads and environmental risks. This is critically important for zones near nuclear power plants [Andrushchenko et al. 2020, Brovko and Brovko 2025, Brovko et al. 2025]. Literature data indicates that even minor vertical displacements (on the order of a few millimeters) can significantly impact infrastructure safety. Combined geoinformation and interferometric methods are therefore essential for stuying territories around the Rivne NPP.

2. Methodology and results

2.1. General characteristics of the Varash municipal territorial community (MTC), Ukraine

The Varash municipal territorial community (MTC) (Fig. 1) is one of the largest and most developed communities in Rivne Oblast. Its administrative center is the city of Varash, which was known as Kuznetsovsk until 2016. The community was established on 26 October 2018, through the annexation of the Zabolottia Village Council of Volodymyrets district to the Varash City Council of regional subordination [Stupen et al. 2023].



Source: Author's own study

Fig. 1. Diagram of the location of the Varash territorial community and its composition

According to data from the Rivne Regional State Administration, the area of the Varash territorial community (TC) is 600.1 km², with a population of approximately 52,994 people. The community's territory includes the city of Varash and surrounding villages, which engendering diversity in both economic and social structures.

The community is located in the southwestern part of Rivne Oblast, bordering Zhytomyr and Volyn regions. Its territory features a varied landscape, including forested areas, rivers, and lakes, creating favorable conditions for the development of agriculture, tourism, and recreation.

The natural resources of the community include fertile soils rich in organic matter that support agricultural development. Forested areas provide not only timber but also opportunities for forestry and recreational tourism. Rivers and lakes are important sources of water, and are key to fishing, and leisure activities [Prylypko et al. 2019, Talerko et al. 2025].

The economy of the Varash TC is based on industry, agriculture, and the service sector. The city of Varash is an important industrial center, hosting enterprises in the nuclear energy sector, particularly the Rivne Nuclear Power Plant, one of the main energy sources in Ukraine (Fig. 2). This facility provides a significant number of jobs and contributes to the development of related industries.

Source: Author's own study

Fig. 2. Exterior view of the Rivne Nuclear Power Plant

According to Ukrainian legislation, territories with nuclear power plants are classified as observation zones. This status entails special conditions for residential life and economic activities. In particular, residents of these areas are entitled to socio-economic compensation for the risks associated with nuclear facilities, including benefits for electricity consumption.

The community focuses its agriculture on the cultivation of cereals, industrial crops, and livestock farming. Developed infrastructure, including roads, transport networks, and utilities, supports the efficient functioning of the economy and meets the needs of the population.

Varash territorial community (TC) places significant emphasis on the development of education, healthcare, and culture. The community hosts general education schools, preschool institutions, and extracurricular educational establishments, ensuring access to quality education for children and youth.

The healthcare system includes hospitals, outpatient clinics, and other medical facilities that provide medical services to residents. Special attention is given to the development of primary healthcare and disease prevention programs.

The cultural sector of the community features cultural centers, libraries, museums, and other institutions that preserve and develop cultural heritage, organize leisure activities, and foster creativity among residents.

Varash TC is actively working to improve the social living conditions of its residents. Social protection programs and support for low-income populations are being implemented, as are employment and entrepreneurship development initiatives.

The administrative management of the community is carried out by the Varash City Council and its executive bodies. Strategic documents, such as the Varash TC Development Strategy, which defines the community's development priorities across various sectors up to 2027, are put into action.

Varash TC's development prospects are linked to the integration of modern technologies, infrastructure development, preservation of natural resources, and improvement of residents' quality of life. Particular attention is paid to developing f green energy, improving energy efficiency, and setting up a favorable environment for small and medium-sized businesses.

Thanks to strategic planning, active community participation, and support from state and international partners, Varash TC has the potential to become a model for successful development of united communities in Ukraine.

2.2. Technology for building the geographical information system of the Varash territorial community based on remote sensing data

To create a comprehensive geoinformation model of the Varash territorial community, a complex multi-stage technological process was implemented. It encompassed the acquisition, preprocessing, geospatial transformation, and subsequent vectorization of very high-resolution satellite data. This process comprises downloading source materials with the use of the SASPlanet software, which is an efficient tool for aggregating satellite imagery from various open and commercial sources. The program allows interaction with numerous cartographic services and enables downloading tiles into a local cache for further offline work.

After loading the SASPlanet environment, the data source was selected. For this study, the Google Satellite resource was chosen for its high level of detail and good photometric stability, attributes particularly important for vectorization tasks. Scaling was set to Zoom levels 15–19 in order to maintain an optimal balance between the area size and image resolution. The actual capturing of the territory was performed by selecting the area of interest using specialized selection tools. The territory was limited with a polygonal selection method to ensure accurate reproduction of the community's boundaries. The selection parameters specified the coordinates of the polygon's vertices, the output file format, the coordinate system (WGS84), the zoom levels, and the additional parameters for future downloads.

The satellite data acquisition process involved downloading sets of tiles using a multi-threaded access system. An optimal configuration of 5–10 threads ensured high download speed and minimized the likelihood of data loss. The 'Skip existing tiles' and 'Retry errors' options reduced the overall download time and prevented gaps in the tile array. Once the complete set of tiles for the territory had been accumulated, they were merged into a single raster sheet. At this stage, a unified geospatial raster in ECW format was created This format features efficient compression without significant loss of visual quality and is convenient for use in geoinformation systems. Alongside the raster file, a .wld georeferencing file was automatically generated, enabling precise positioning of the image within the WGS84 coordinate system (Fig. 3).

Source: Author's own study

Fig. 3. Downloaded satellite image of the Varash territorial community

The created raster was loaded into the QGIS environment. When opened, the software automatically recognized its spatial reference (EPSG:4326) and displayed the image in the correct geographic location. The initial stage involved visual processing that included adjustments to brightness, contrast, and colour balance in the 'Symbology' tab. These adjustments were important for enhancing contour clarity, which directly affected the accuracy of subsequent vectorization.

Next, vector layers were created to form the structure of the future spatial database. The geometry type (polygon, line, or point) was defined, and an attribute table was created containing three main fields: ID (integer), Name (text field up to 80 characters), and Type (object classification). Vectorization was carried out in editing mode through the step-by-step digitization of features visible on the satellite image. Each polygon, line, or point was accompanied by an attribute description, resulting in a logically organized information structure.

In the Varash TC GIS project, the following main vector layers were planned:

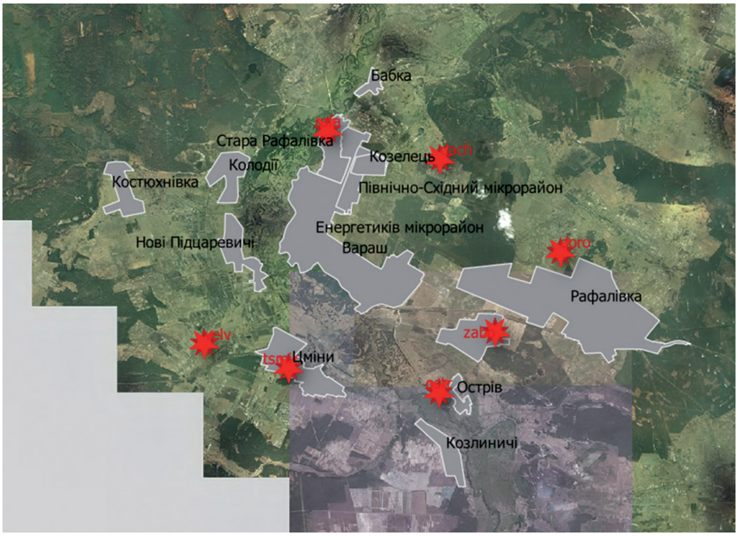
- Points of interest of Varash TC, displaying all major point-type objects,
- Road network_Varash TC,
- Hydrography_rivers_Varash TC,
- Railway network_Varash TC,
- Buildings_Varash TC,
- Hydrography_Varash TC,
- Settlements_Varash TC,
- Vegetation_Varash TC,
- Geodynamic polygon_Varash TC.

During vectorization, a set of vector layers was created to fully represent the territorial organization of Varash TC. In the vegetation layer, 2,534 polygonal objects were vectorized, representing forests, shrubs, and other green areas. The digitally reproduced settlements layer contains 54 polygons corresponding to the settlement boundaries. Polygonal hydrographic objects were recorded in a total of 1,207, including lakes, ponds, and other water bodies. A large-scale vectorization of buildings was carried out in the largest settlements, covering 19,930 objects of various shapes and sizes. The river network included 1,794 linear objects representing rivers, tributaries, and drainage channels. The linear road network consisted of 8,171 road segments of different types. The points of interest layer comprised 721 objects.

A separate stage was dedicated to creating a specialized geodynamic polygon layer, consisting of points representing comprehensive geodetic stations located around the Rivne Nuclear Power Plant [Savchyn et al. 2025].Precise coordinates were entered for each point, and the attribute table included an additional field with hyperlinks to photographs of the stations. This enhanced the layer's visualization and functionality.

Together, all layers form a comprehensive geoinformation system for Varash TC, in which each object has geometric properties and attribute descriptions that enable further spatial analysis, landscape change monitoring, thematic map creation, and research activities (Figs. 4 and 5).

After the vectorization was completed, all the edits were saved, and the appearance of the layers was optimized by adjusting the symbology, color palettes, and labels. This has polished the visual presentation of the created GIS . As a result, a comprehensive spatial database was formed, accurately representing the territory of Varash TC in a detailed, structured, and analytically usable format (Fig. 6).

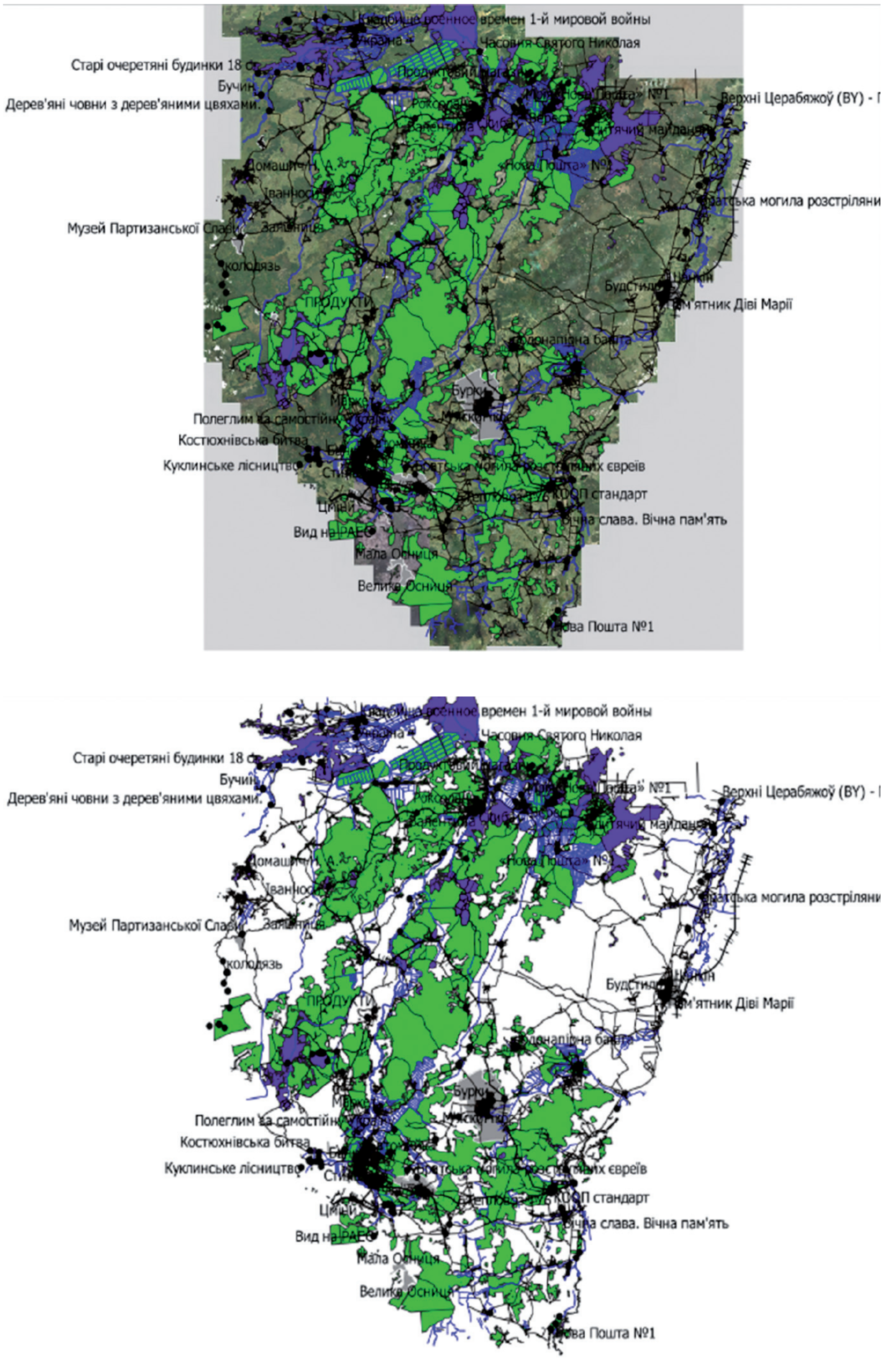


Source: Author's own study

Fig. 4. Layer of geodetic points of the geodynamic polygon

Source: Author's own study

Fig. 5. Exterior view of the comprehensive geodetic station



Source: Author's own study

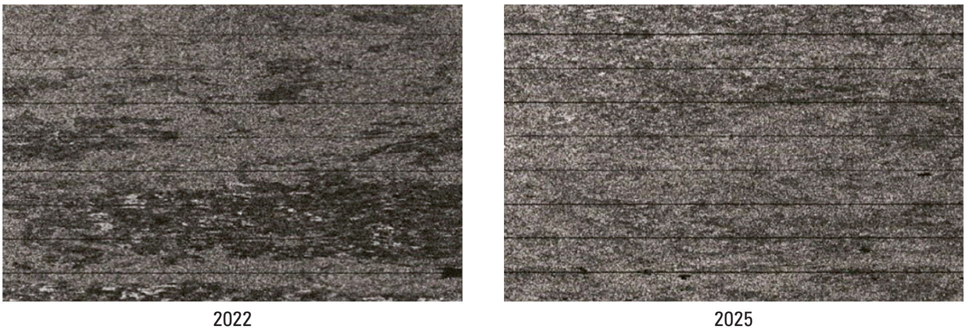
Fig. 6. General view of all layers in the Varash TC GIS

The remote sensing data sources selected for this study were identified based on their spatial resolution, temporal availability, and suitability for the long-term monitoring of territories adversely impacted by human activity. Very-high-resolution optical satellite imagery (Google Satellite) was selected to accurately vectorize infrastructural, hydrographic, and land-use objects within the Varash territorial community. Radar Sentinel-1 SLC products were chosen due to their open accessibility, high temporal revisit frequency, and proven effectiveness in monitoring deformation using interferometric techniques. The combination of optical and radar data allows for complementary analysis, providing a detailed spatial representation supported by a quantitative assessment of ground surface dynamics.

2.3. Methodology for determining vertical land displacements around the Rivne Nuclear Power Plant

The initial stage involved acquiring Sentinel-1 satellite radar images in order to construct interferograms. Source products of the SLC (single look complex) type were downloaded, containing both phase and amplitude information of the signal, critical for interferometric analysis. A pair of images over the same area was selected for deformation analysis – Master and Slave – acquired on different dates: 10 October 2022 and 15 August 2025.

The appearance of the loaded image pair is shown in Figure 7.

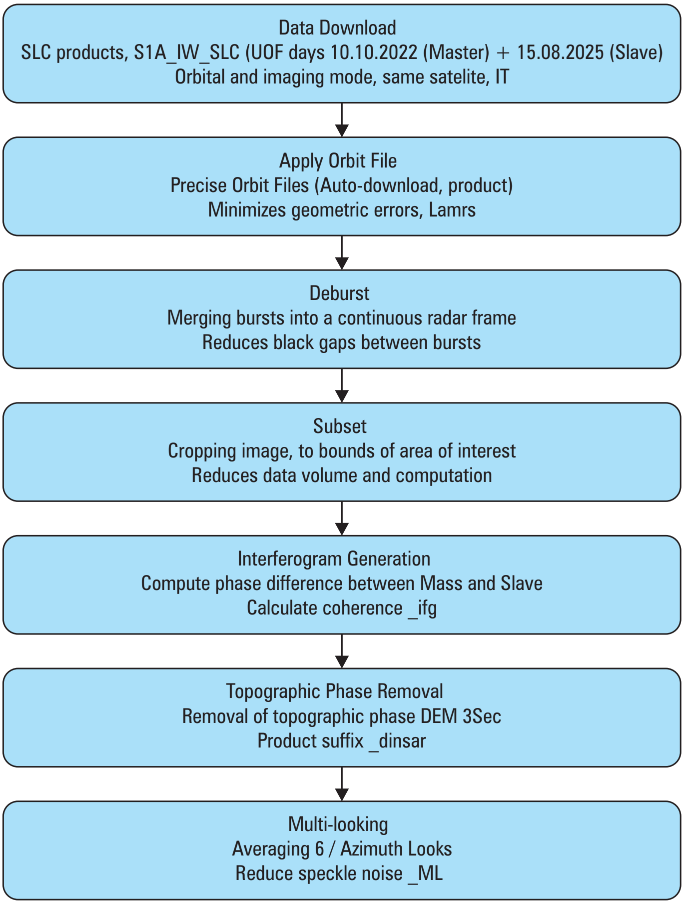


Source: Author's own study

Fig. 7. Appearance of the loaded pair of radar images

Both images were acquired by the same satellite (S1A) in Interferometric Wide Swath (IW) mode and on the same orbit, ensuring correct geometric alignment during subsequent processing stages. The downloaded files were kept in ZIP format for further use in the SNAP software (Fig. 8).

At the next stage, precise orbital data (Precise Orbit Files) were applied to correct satellite trajectory errors and minimize geometric distortions in the images. This process included automatic downloading and integrating data from ESA to create a new product with the suffix _Orb, which was then used for further processing. The 'Do not fail if new orbit file is not found' option was enabled, allowing computation to continue even if the latest orbital data were unavailable.



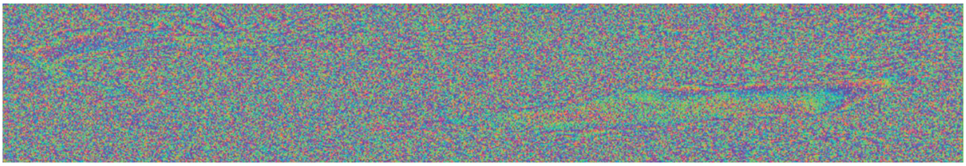
Source: Author's own study

Fig. 8. Technological workflow for processing radar satellite images in SNAP

The Deburst operation was performed to merge individual Sentinel-1 SLC bursts into a continuous radar frame, eliminating black gaps at burst boundaries and ensuring signal integrity. To optimize processing of large areas, the scene was cropped to the boundaries of the area of interest using the Subset tool, which has significantly reduced data volume and computation time without loss of information.

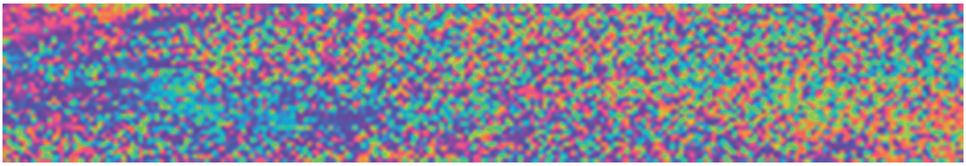
The Coregistration stage was carried out to accurately align the Master and Slave images. The sub-pixel positioning of each point in the Slave image relative to the Master product ensured high-precision pixel correspondence and minimized phase image errors. Simultaneously, polarization consistency (VV) was verified for both scenes, guaranteeing stable matching. In Advanced Settings, the Search range in azimuth and Search window in range parameters were increased to compensate for the spatiotemporal differences between the scenes. As a result, a stack of two aligned images was obtained.

Interferogram was generated by calculating the phase difference between the Master and Slave images (Fig. 9). Coherence was also computed to assess the interferogram quality: higher coherence indicates more reliable phase data. To isolate the actual surface deformations, topographic phase removal was carried out using the SRTM 3Sec digital elevation model (DEM). The resulting product, with the suffix _dinsar, contained only the differential surface phase (Fig. 10).



Source: Author's own study

Fig. 9. Result of interferogram construction for the area around the Rivne Nuclear Power Plant for 2022–2025

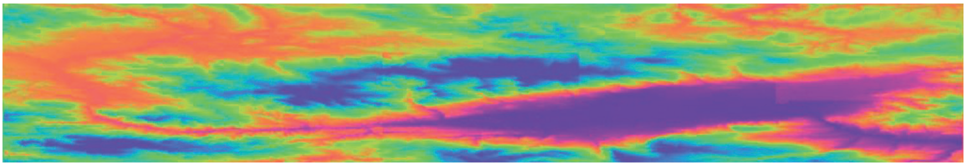


Source: Author's own study

Fig. 10. Interferograms of the area around the Rivne Nuclear Power Plant for 2022–2025 after topographic phase removal

To reduce noise and enhance the visibility of the interferogram, multi-looking algorithm was applied, averaging every 6 pixels in the range direction (Range Looks) and 2 pixels in the azimuth direction (Azimuth Looks). This procedure reduced speckle noise and produced a smoother phase field. Subsequently, phase filtering was performed using the Goldstein method, which suppressed high-frequency noise components without losing the overall structure of the interferogram. The resulting product received the suffix _flt.

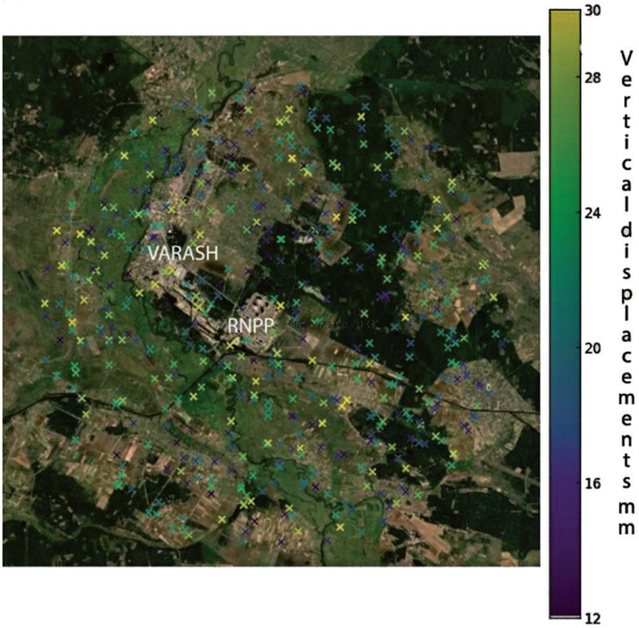
Phase unwrapping was then carried out to convert cyclic values from 0 to 2π into a continuous phase field. The SNAPHU module was used, with the filtered interferogram (_flt) as input. After unwrapping, a product with the suffix _unw was generated, allowing quantitative assessment of surface displacement (Fig. 11). For the Sentinel-1 satellite, with a wavelength of $\lambda \approx 5.6$ cm, a phase change of 2π corresponds to a displacement of approximately 2.8 cm in the line-of-sight direction.



Source: Author's own study

Fig. 11. Results of interferogram phase unwrapping for the area around the Rivne Nuclear Power Plant

The final stage involved geocoding (Terrain Correction) using the Range-Doppler method, referenced to the WGS84 projection with a pixel size of 18 m. The resulting product, with the suffix _TC, was ready for integration into a GIS and for creating a vertical displacement map. Based on the obtained data, vertical deformations within the study area ranged from 12 mm to 30 mm over the period from 2022 to 2025, confirming the stability of most of the area around the Rivne Nuclear Power Plant (Fig. 12).



Source: Author's own study

Fig. 12. Map of vertical land displacements around the Rivne Nuclear Power Plant from 2022 to 2025

All stages of the technological process were carried out sequentially, with accuracy control at each operation, ensuring the production of a high-quality interferometric product suitable for quantitative analysis of ground surface deformations and the construction of reliable vertical displacement maps.

3. Discussion

The conducted study demonstrates that integrating high-resolution satellite imagery, remote sensing techniques, and GIS technologies is effective in conducting a comprehensive spatial analysis of the Varash City Territorial Community (TC) and for monitoring geodynamic stability around the Rivne Nuclear Power Plant (NPP). Creating a multi-layered GIS provides a structured framework for representing the physical, infrastructural, and environmental components of the community, offering a valuable tool for urban planning, environmental monitoring, and resource management.

The interferometric analysis of Sentinel-1 radar images enabled the detection of subtle vertical displacements within the study area over a three-year period. The observed vertical deformations, ranging from 12 mm to 30 mm, suggest that the majority of the territory exhibits stable geodynamic behavior. These results are consistent with the expectations for areas surrounding well-monitored nuclear facilities, where extensive engineering and geological assessments are conducted to ensure long-term stability. The precision of the differential interferometric synthetic aperture radar (DInSAR) methodology, combined with multi-looking, phase filtering, and phase unwrapping, proved sufficient for identifying small-scale displacements that could be overlooked using conventional ground-based surveys.

The study also highlights the value of combining thematic GIS layers with geodynamic monitoring data. By linking infrastructure, settlements, vegetation, and hydrography to the geodetic points of the geodynamic polygon, decision-makers can visualize potential risk zones and prioritize monitoring and mitigation efforts. This integration emphasises the importance of spatially explicit information for both local governance and emergency planning.

However, several limitations should be considered. The accuracy of interferometric measurements can be affected by vegetation cover, atmospheric disturbances, and temporal decorrelation, particularly in densely vegetated or rapidly changing landscapes. Additionally, the use of Sentinel-1 imagery, while it offers frequent revisits and wide coverage, is limited by its spatial resolution (typically ~5–20 m), which may obscure very localized displacements. Future studies could benefit from incorporating higher-resolution radar imagery or combining DInSAR with ground-based geodetic measurements, such as GNSS and leveling, to improve precision and validation.

From a broader perspective, the established GIS framework and methodology for monitoring vertical displacement provide a replicable model that can be adopted by other Ukrainian territorial communities, particularly those in proximity to critical infrastructure. Regular updates of satellite imagery and continuous monitoring can support proactive land management, the early detection of potential geohazards, and sustainable development planning. Furthermore, integration with socio-economic and environmental data could facilitate multi-criteria assessments for infrastructure development and risk management.

The integrated methodological framework proposed in this study demonstrates a high level of transferability and can be effectively adapted to other regions under strong anthropogenic pressure. The combination of high-resolution optical satellite imagery, GIS-based spatial modeling, Sentinel-1 InSAR analysis, and ground-based observations from comprehensive geodetic stations provides a universal toolset applicable to a wide range of critical infrastructure objects. These include not only nuclear power plants but also hydroelectric dams, mining and subsidence-prone areas, large industrial zones, waste storage facilities, and transport infrastructure corridors. The adaptability of the approach lies in its modular structure, allowing individual components to be scaled or modified depending on regional geological conditions, infrastructure type, and monitoring objectives.

Similar satellite-based monitoring approaches have been widely applied in international case studies, particularly for assessing the geodynamic stability of areas near nuclear facilities in Europe and Asia, monitoring subsidence in mining regions, and evaluating deformation of large dams and urban agglomerations. Compared to these studies, the Rivne NPP case serves as a valuable regional example that integrates long-term InSAR observations with a detailed municipal-level GIS and a network of comprehensive geodetic stations. This integration not only enables deformation detection, but also facilitates its interpretation in the context of land use, infrastructure distribution, and environmental factors, thereby extending existing international methodologies toward a more holistic assessment of territories affected by technology.

4. Conclusions

The research implemented a comprehensive approach for creating a geographic information system (GIS) of the Varash City Territorial Community and analyzing vertical land displacements around the Rivne Nuclear Power Plant. Modern methods of Earth remote sensing, satellite radar imaging, and digital image processing were applied to acquire highly accurate and structured spatial data, suitable for detailed spatial analysis and informed decision-making.

High-resolution satellite images were downloaded and processed using SASPlanet and QGIS software. As a result of vectorization, a series of thematic layers were created, including road and railway networks, hydrography, buildings, settlements, vegetation, points of interest, and geodynamic polygons. Each layer contains information about attributes and geometric characteristics of objects, ensuring the possibility of further analysis, landscape change monitoring, and thematic map generation. Special attention was given to the creation of a geodynamic polygon layer with precise locations of comprehensive geodetic stations around the Rivne NPP, as it improves the functionality and visualization of the GIS.

In a broader scientific context, the obtained results can contribute significantly to existing international studies on deformation monitoring and infrastructure safety. Unlike many previous works focused primarily on deformation detection, this study emphasizes the integration of geodetic, geophysical, and environmental data within a unified GIS framework at the municipal scale. Such an approach enhances both the interpretability of deformation signals and their applicability to spatial planning, risk assessment, and long-term monitoring strategies. Consequently, the Rivne NPP case study contributes to the development of transferable methodologies for assessing the stability of territories affected by technology worldwide.

The interferometric analysis method was applied to Sentinel-1 satellite radar images within the study of vertical land displacements. This involved generating interferograms, followed by multi-looking, phase filtering, phase unwrapping, and geocoding - a series of steps that allowed the creation of high-precision maps of differential vertical deformations for the period 2022–2025. The magnitude of vertical displacements in the study area were found to range from 12 mm to 30 mm, confirming the stability of most of the territory around the Rivne Nuclear Power Plant and the absence of critical geodynamic processes during this period.

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