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Original Contribution

PRESENT TECHNIQUES FOR SPATIOTEMPORAL ANALYSIS OF EARTH DEFORMATIONS USING DINSAR AND GNSS

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ABSTRACT: *One of the significant problems facing Earth sciences is the quantitative description and analysis of the dynamics of the Earth's surface. A key requirement in solving this fundamental question is the precise determination of the displacements and deformations caused by various geodynamic processes of natural or anthropogenic origin.*

In recent decades, Earth observation has become widely used in disaster risk management – including preparedness, response, recovery and mitigation. Its role in disaster response is particularly valuable, as it provides critical information for researchers and decision-makers.

Earth observation is the collection of data about the planet through remote sensing technologies, which are often complemented by ground-based surveys. This approach has fundamentally changed the way we perceive the world, enabling timely and accurate mapping and monitoring of phenomena on a large scale.

An established method for continuous monitoring of earth deformations is the use of data from active radar remote sensing. Synthetic Aperture Radar (SAR) provides information that serves as the basis for the construction of interferometric images (IFIs) by quantifying the displacements of the Earth's surface within a specified time interval using the technique of differential radar interferometry (DInSAR) by analysing the phase differences between radar images taken at different times.

KEY WORDS: *Strain monitoring, InSAR, GNSS, Radar interferometry, Geodynamic processes, Risk management, Natural disasters, Dams and landslides, Integrated observations, Spatial analysis.*

1. Introduction

Monitoring of land deformations is essential for understanding and managing geodynamic processes that affect the natural and built environment [3,4]. Precise monitoring of land surface movements allows for early detection of potentially dangerous phenomena such as landslides, earthquakes, soil subsidence and deformations in critical infrastructure such as dams, tunnels and buildings. Timely identification of such deformations can prevent large-scale damage, economic losses and human casualties.

In recent decades, the development of geodesy and remote sensing has led to the introduction of high-tech methods for monitoring the earth's surface. A special place in this process is occupied by global navigation satellite systems (GNSS) and synthetic aperture interferometry (InSAR) – two complementary approaches that provide precise spatial and temporal measurements of deformation processes. GNSS networks provide high-frequency three-dimensional data with high accuracy at point positions, while InSAR offers the ability to spatially continuously track surface displacements with a range of tens to hundreds of kilometers [5,8].

The rise of satellite missions such as Sentinel-1 (within the framework of the European Copernicus program), TerraSAR-X, COSMO-SkyMed and others, as well as affordable software solutions for radar image processing, has greatly facilitated the integration of InSAR in various fields of applied geodesy, geoinformatics, geology and risk management. In parallel, the development of GNSS technologies and networks for continuous monitoring contributes to reliable and real-time monitoring of critical sites and areas with increased seismic or geodynamic activity.

The present study aims to present an in-depth overview of the methods for monitoring earth deformations using InSAR and GNSS, focusing on their principles of operation, data processing methods, advantages and limitations, as well as on the possibilities for combined application in real engineering and natural scenarios.

By combining theoretical and applied analysis, the text aims to contribute to a better understanding of modern technologies for monitoring the earth's surface and their role in the prevention of natural and man-made disasters. In conclusion, recommendations will be formulated on the practical implementation of combined monitoring systems in Bulgaria and in the international context.

2. Theoretical foundations

2.1 Geodynamic processes and terrestrial deformations

The Earth's crust is a dynamic system, subjected to continuous movements caused by internal and external geophysical processes [6,7]. These processes lead to deformations of the earth's surface, which can be both gradual and cumulative (for example, subsidence, landslides) and sudden (earthquakes, collapses). Geodynamic processes are mainly divided into:

- Tectonic movements related to the movements of lithospheric plates, fault activity, volcanism and elevation or sinking of terrains;

- Anthropogenic impacts, including extraction of underground resources, water abstraction, underground construction and terrain loading;
- Gravity-driven processes, such as landslides, subsidence and erosion;
- Hydrogeological factors related to changes in groundwater, dam levels and changes in pore pressure.

Deformations can be classified according to their direction:

- Vertical deformations – these are changes in the elevation position of the earth's surface relative to a given reference level (for example, a geoid or an ellipsoid), and these changes can be the result of various geophysical, tectonic or anthropogenic processes [7].
- Horizontal deformations – these are changes in the position of points on the earth's surface in the horizontal plane (e.g. in the north-south and east-west directions). They are key to understanding the dynamics of the lithosphere and are observed as a result of a number of geophysical and engineering processes;
- Triaxial deformations – represent the simultaneous change in the position of a point in the three main spatial directions – east-west (X), north-south (Y) and vertical (Z). They unite both horizontal and vertical components of motion and allow a comprehensive analysis of deformation processes in three-dimensional space.

Precise monitoring of these processes requires modern technologies with high spatial and temporal resolution, such as GNSS and InSAR methods.

2.2 Synthetic Aperture Interferometry (InSAR)

The invention and development of radar technology cannot be attributed to a single nation or individual. Rather, it should be considered as a set of numerous developments and improvements, in which many scientists participated in parallel.

The first radar systems appeared in the middle of the 20th century and were mainly used for military and meteorological purposes. With the advancement of synthetic aperture and phase information processing technologies in the 70s and 80s, conditions were created for the development of InSAR as a remote sensing method. The launch of the first radar satellites, such as ERS-1 (ESA) and RADARSAT (Canada), in the 1990s made it possible to regularly collect interferometric data with worldwide coverage.

Interferometry, for its part, is a technique that allows obtaining topographic and kinematic information about the earth's surface from the analysis of the phase difference of different SAR images. The phase of the signal is determined by the distance between the sensor and the target, thus providing information about the relative position of the target relative to the satellite [1].

InSAR is a remote sensing method for measuring changes in the distance between a satellite and the Earth's surface by analyzing the phase difference between two radar images taken from the same location but at different times. The main principles of the method are:

- Synthetic aperture: the radar uses the movement of the satellite to "simulate" a large antenna and thus achieves high resolution;
- Phase interferometry: phase differences between two radar images are used to calculate small vertical displacements of the surface with millimeter accuracy;
- Differential InSAR (DInSAR): a method for isolating deformations by eliminating the influence of topography and other systematic effects.

2.2.1 Mathematical rationale

2.2.1.1Radar signal phase

The radar signal reflected from the Earth's surface and received by the satellite can be described as a complex quantity:

$$S=A\cdot e^{i\phi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where:

- A - amplitude of the signal,
- ϕ - phase that contains information about the distance to the target,
- $i = \sqrt{-1}$.

The phase ϕ is related to the signal path R by the formula:

$$\phi = \frac{4\pi = \pi r^2}{\lambda} R + \phi_0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where:

- λ – the wavelength of the radar signal,
- R - the distance from the satellite to the point on the Earth's surface,
- ϕ_0 - the initial phase (constant).

2.2.1.2 Interferogram

An interferogram is formed by multiplying one complex signal complexly conjugated into another signal received at different times:

$$I=S_1 \cdot S_2^{*}=A_1 A_2 e^{i(\phi_1-\phi_2)} \text{.............................(3)}$$

where:

- S_1, S_2 are the complex signals from the first and second images, obtained by the formula (1) about S_1 and S_2;
- S_2^{*} means complexly conjugated;
- A_1, A_2 are the amplitudes of the signal;
- ϕ_1, $\phi 2$ are the phases of the signals.

This is how the phase difference is obtained $\Delta\phi=\phi_1-\phi_2$, which contains information about changes in the distance between the two moments of survey and contains information about the terrain, changes in height and deformations of the earth's surface that have occurred between the two measurements.

After the interferogram was created, the phase difference between the two radar images was presented in the range of $-\pi$ to $+\pi$ radians. This is due to the nature of the complex exponent used in radar interferometry, in which the phase is a periodic quantity.

The coiled phase thus obtained does not give direct information about the actual physical displacements or relief differences, because it does not include the entire number of cycles of 2π through which the phase has passed, since it is limited in the interval [-180º, 180º].

The phase unwinding process aims to restore a continuous phase surface by adding or subtracting an appropriate number of full cycles of 2π to calculate the so-called absolute phase.

2.2.1.2.1 Components of phase difference

The phase difference $\Delta\phi$ can be decomposed into several main components:

$$\Delta\phi=\phi_{def}+\phi_{topo}+\phi_{atm}+\phi_{noise} \text{..................................(4)}$$

where:

- ϕ_{def} - phase component due to deformations of the earth's surface (the desired magnitude),
- ϕ_{topo} - phase component caused by topographic relief,
- ϕ_{atm} - phase deviations due to atmospheric conditions (humidity, pressure),
- ϕ_{noise} - noise and random errors.

2.2.1.3 Differential InSAR (DInSAR)

To isolate the phase associated with deformations, the differential technique is used, in which the topographic effect is corrected by applying a digital relief model (DEM):

$$\Delta\phi_{def}=\Delta\phi-\phi_{topo}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

This leaves phase information that is directly converted into distance changes ΔR:

$$\Delta R = \frac{\lambda}{4\pi}\Delta\phi_{det}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

The measured ΔR is the projection of the displacement of the earth's surface in the direction of radar viewing (LOS).

The main advantage of InSAR is the ability to retrospectively analyze archival data and create time series of deformations. Limitations include sensitivity to vegetation cover, weathering, and loss of coherence in sudden changes in the landscape, and is particularly effective for:

• Tracking landslides and urbanized areas;
• Monitoring of dams and reservoirs;
• Measurement of the consequences of underground resource extraction;
• Evaluation of post-seismic deformations

Since DInSAR measures displacements in the LOS direction only, it is often necessary to combine data from different viewing angles or integrate with GNSS data to achieve a three-dimensional estimation of strain.

2.3 Global Navigation Satellite Systems (GNSS)

GNSS (Global Navigation Satellite Systems) include navigation systems such as GPS (USA), GLONASS (Russia), Galileo (EU) and BeiDou (China), which provide continuous three-dimensional coordinates of objects on the earth's surface. In geodesy and strain monitoring, GNSS is used through [9,10]:

• Permanent stations, part of global or national reference networks (e.g. EUREF, IGS);
• Local GNSS networks built around critical infrastructure sites;
• Kinematic and static measurements, in which the movement of points in time is monitored.

GNSS allows:

• Measurement of horizontal and vertical movements with an accuracy of a few millimeters;
• Real-time or near-real-time monitoring, especially important in emergency situations;

• Integration with geodetic and cartographic systems to create deformation models.

The disadvantages of GNSS include the point nature of the measurements (it does not give a spatial picture), the need for physical access to the measurement point, as well as sensitivity to local interference in the signal (multipath, loss of visibility, etc.).

Taken together, GNSS and InSAR are complementary technologies that allow for efficient observation of the Earth's surface with high accuracy. While GNSS provides continuous temporal observation at specific points, InSAR provides spatial context and the ability for large-scale analysis. Their joint application offers a significant improvement in the reliability and scope of monitoring of earth deformations, especially in areas with an increased risk of geodynamic phenomena.

3. Methodology

3.1 InSAR Data Processing

The processing of synthetic aperture radar (SAR) data for the purpose of monitoring ground deformations includes several main stages:

- Selection of appropriate radar images- Pairs of images taken at different time moments are used, but with a close orbital configuration. Popular sources are the Sentinel-1, TerraSAR-X and COSMO-SkyMed satellites.
- Interferogram generation- By combining the phase information from the two SAR images, an interferogram is created that contains information about changes in the distance between the satellite and the Earth's surface.
- Correction of the topographic effect-Topographic elevation causes a phase that is not associated with deformations. This effect is eliminated using a digital elevation model (DEM).
- Filtering and increasing coherence-Spatial filters are applied to reduce noise and improve the quality of the interferogram.
- Phase Difference Analysis (DInSAR)-Differential interferometry allows the extraction of phases corresponding only to deformations, excluding other influences, such as atmospheric effects.
- Generate strain maps and time series- Based on the corrected interferograms, accurate values of vertical displacements are calculated for each pixel in the observation area.
- Use of software packages- Popular tools include ESA SNAP, GMTSAR, StaMPS, and others that allow for automation and precise machining.

3.2 GNSS Data Processing

To obtain three-dimensional coordinates and accurately measure earth motions using GNSS, the process includes:

- Installation and calibration of GNSS stations - Permanent or temporary stations are located in key places where deformations are expected.
- Collection of satellite observations- Time series of satellite signals are recorded and prepared for post-processing.
- Post-processing of observations- Through specialized software (e.g. GAMIT/GLOBK, Bernese, RTKLIB), raw data is processed to eliminate errors caused by the atmosphere, clock deviations, etc.
- Calculation of three-dimensional coordinates and displacements- Time series analysis allows you to identify trends and anomalies in the movement of points.
- Integration with geodetic and geodynamic models- GNSS data is embedded in spatial models for a better understanding of dynamics.

3.3 Integration of InSAR and GNSS data

Combining the two methods allows you to achieve a synergistic effect:

3.3.1 Validation and calibration of InSAR results

The results of InSAR analysis can be influenced by various sources of error, such as atmospheric effects, surface noise, geometric and orbital imperfections. To achieve higher accuracy and reliability, InSAR results need to be validated and calibrated with independent and more accurate measurements.

- GNSS (Global Navigation Satellite System) measurements provide direct and very precise information about the three-dimensional positioning of specific points on the Earth's surface. Since GNSS systems have accuracy within a few millimeters to centimeters, they are used as reference data in the validation of InSAR results.

- In practice, GNSS measurements are carried out at key control points that are located in the monitored monitoring areas. These points serve to:

• **Correction of systematic deviations** in InSAR data that may occur due to weather conditions, orbital errors, or various interferometric artifacts. Table 1 presents a specific type of deviation and a correction method.

• **Confirmation of the accuracy and reliability** of the observed deformations by comparing the vertical and horizontal components of the GNSS and InSAR measurements. These steps provide a scientific basis for the credibility of observed deformations needed for decision-making and risk assessment in engineering, hydrological and environmental facilities.

• **Calibration of InSAR models** is a process of optimization and correction of phase data obtained from satellite radar measurements in order to increase the accuracy of the inferred displacements of the earth's surface. This is especially important for applications such as monitoring dams, landslides, and infrastructure facilities where measurement accuracy is extreme.

Table 1

№	Error	Example from a Real Time	Impact on the Interferogram	Correction Method
1	**Tropospheric Refraction**	Earthquake in Nepal (Sentinel-1)	Vertical “Noise” in Mountainous Area	Models from GNSS, ERA5, GACOS
2	**Ionospheric Disturbances**	Earthquake in Indonesia (ALOS-2, L-band)	Color Artifacts, Spatial Variations	Split-spectrum technique, Dual-pol correction
3	**Orbital Error**	Deformations in the Po Valley, Italy	Linear Phase Gradient	Precise Orbit Determination (POD), Polynomial Regression
4	**Topographic Error**	Landslide in Norway with inaccurate DEM	Residual Phase, Especially on Slopes	Use of More Accurate DEM (TanDEM-X, LiDAR)
5	**Temporal Decorrelation**	Ticha Dam Area	Reduced Coherence Due to Seasonal Changes	Filtering, SBAS, Short Time Intervals
6	**Geometric Decorrelation**	Steep Slopes Around Ticha Dam	Loss of Coherence, Noise	Selection of Optimal Baseline Interval
7	**Layover/Shadow Effects**	Urban Areas and Rock Outcrops in the Ticha Dam Region	Inability to Perform Accurate Phase Analysis	Exclusion of Affected Areas, 3D SAR Techniques

This integration of GNSS and InSAR technologies significantly increases confidence in the results and is particularly important in the monitoring of critical engineering facilities and natural disasters, where accurate information on earth movements is key.

3.3.2 Complementarity of spatial and temporal scope

InSAR technology provides a detailed and broad spatial picture of deformations on the earth's surface with high spatial resolution (usually from several meters to tens of meters). This allows for effective monitoring of large areas and detection of local and regional changes in the terrain. However, InSAR is limited in terms of temporal resolution and frequency of observations, which depends on the parameters of the satellite cycle (e.g. 6, 12 or 24 days).

On the other hand, GNSS networks provide continuous and highly precise time series of three-dimensional coordinates at selected control points. GNSS measurements are carried out at a frequency of several seconds to minutes, which allows for a detailed analysis of the dynamics and speed of deformations in real time. This high-frequency information is key to recognizing fast events and building dynamic models of Earth motions.

The combination of InSAR's large-scale spatial scope and precise GNSS time series makes it possible to:

• **Enriching the spatial density of observations** by using InSAR maps, calibrating and validating them through point GNSS data.

• **Improve temporal analysi**s of strains by integrating continuous GNSS measurements with time-limited InSAR interferograms.

• **Multimodal monitoring** that makes it easy to recognize and model complex processes, such as seasonal fluctuations, rapid collapses, or emergency events.

• **Build hybrid forecasting and early warning models** that use GNSS real-time series to update InSAR-based spatial models.

This integration is especially useful in critical infrastructure sites and natural areas, where both a wide spatial overview and detailed temporal information about the dynamics of the Earth's movements are needed.

3.3.3 Creating 3D Warp Models

Combining spatially extensive InSAR data with precise three-dimensional GNSS measurements allows the construction of reliable and highly accurate 3D models of ground deformations. These models represent the full vector character of the movements, including both the vertical and horizontal components of the deformation. The main idea is to combine the one-dimensional measurements of InSAR in the direction of observation (LOS) with the three-dimensional coordinate series of GNSS. In this way, the limitations of each individual method are overcome and a complete spatial and temporal picture of the earth's movements is achieved.

3.3.4 Improvement of monitoring systems

The integration of InSAR and GNSS data through modern algorithms and modeling significantly increases the reliability and sensitivity of Earth deformation monitoring systems. Combined data make it possible to overcome the limitations of each individual method, using their complementary advantages.

4. Conclusion and Recommendations

The present study has outlined the mathematical foundations and practical value of the combined use of Interferometric Synthetic Aperture Radar (InSAR) and Global Navigation Satellite Systems (GNSS) for monitoring ground deformations. The analysis highlighted the key advantages of the integrated approach, including the high spatial resolution of InSAR and the three-dimensional temporal accuracy of GNSS, as well as the potential for mutual data verification.

Based on the theoretical analysis, the following recommendations can be made regarding the implementation of combined monitoring systems:

- **Technological and Methodological Recommendations**
  - Develop standardized protocols for the integration of InSAR and GNSS data, including algorithms for combined processing (e.g., Kalman filtering, SBAS-InSAR with GNSS constraints).
  - Create automated platforms for deformation detection and analysis, based on cloud computing and machine learning technologies.
  - Utilize long time series from Sentinel-1 satellites in combination with continuously operating GNSS stations for the calibration and validation of ground motion data.

- **Applied Recommendations for Bulgaria**
  - Expand the national GNSS network with the strategic placement of stations near critical infrastructure objects (dams, mining areas, landslides).
  - Establish a national geodetic monitoring program, funded through public and European sources, with a focus on InSAR/GNSS integration.
  - Create an interagency platform for data exchange and interpretation, involving the Bulgarian Academy of Sciences (BAS), the Ministry of Regional Development and Public Works (MRDPW), the Ministry of Environment and Water (MOEW), and the General Directorate for Fire Safety and Civil Protection (GDFSCP) under the Ministry of Interior.

- **International Aspects and Best Practices**
  - Bulgaria should actively participate in initiatives such as the European Ground Motion Service (EGMS) and the Copernicus Emergency Management Service (EMS).
  - It is necessary to strengthen participation in scientific consortia and networks (e.g., EPOS, GEO) to facilitate the exchange of best practices and technologies.
  - Cross-border pilot projects should be initiated, applying InSAR-GNSS monitoring in seismically active or erosion-prone regions of the Balkans.

Summary

Combined InSAR-GNSS systems represent an effective tool for the early detection and monitoring of geodynamic processes that pose risks to infrastructure and populations. The practical implementation of such systems requires not only technological support but also institutional coordination, sustainable funding, and the availability of expert capacity. In this context, Bulgaria has the potential to develop a national framework for satellite-based geodetic monitoring aligned with international best practices.

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