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## Integration of InSAR Technology in the Stability Assessment of Load Bearing Structures\*

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*Non-destructive condition monitoring of buildings and other civil engineering structures is a challenging issue. Even though many measuring techniques have been developed in the last decades, still, significant knowledge gaps exist in building monitoring. One of the major problems of structural condition assessment is that the measured parameters are evaluated only occasionally. However, there is just a limited number of techniques available that can provide continuous monitoring of the technical condition of structures and provide time-series information on their construction stability. The main purpose of the paper is to introduce a diagnostic technique that has the potential to overcome the above-mentioned shortages by combining periodic non-destructive measurements with continuous monitoring obtained by a practical application of satellite remote sensing. Synthetic Aperture Radar (SAR) has many advantages that are worth being considered by structural engineers for their routine practice of assessing the stability of existing structures. Our focus is to provide insight into the theory of Interferometric Synthetic Aperture Radar (InSAR) technology and show its combined application with other condition assessment techniques via a real case study. The efficiency of the proposed methodology was shown by the comparison of displacement results of a water tower obtained by InSAR monitoring, conventional geodetic survey and numerical analysis.*

**Keywords:** civil engineering, structural monitoring, InSAR, Sentinel-1, non-destructive testing.

### Introduction

InSAR (Interferometric Synthetic Aperture Radar) is a technique mainly used for mapping ground deformation using radar images of the Earth's surface that are collected from orbiting satellites. Although InSAR technology was introduced several decades ago, its extensive utilization was hindered by the absence of freely available datasets. This situation completely changed by the launch of the Sentinel-1 (S1) constellation, which is part of the Copernicus program of the European Space Agency (ESA). It is the first SAR satellite constellation, that provides freely available data with frequent revisits, which makes S1 products an ideal input for interferometric (InSAR) processing. It is a significant advancement, as previous ESA missions (ERS, Envisat) did not maintain regular revisit times or consistent coverage.

S1 images are available from October 2014, with a 12 days frequency, that had been upgraded to 6 days repeat cycles cycle by the launch of the second satellite in early 2016. However, over certain areas and high latitudes the 12 days revisit remains the norm to date. The satellite pair shares the

same orbit plane, and both use a C-band Synthetic Aperture Radar (SAR) instrument, where the wavelength is ca. 5.6 cm (5.405 GHz). S1 is operating in a wavelength that is not interfering with cloud cover and unaffected by the lack of illumination, allowing constant operation day, or night. Above land surfaces, the most common operational mode is the interferometric wide swath (IW) with an approximate 15 meters of spatial resolution, where a single image frame covers 250×250 kilometers.

As part of the programme, ESA provides a large online, and free database of the imagery. Concerning the future of the programme, funding and plans go as far forward as the 2030s, with new missions under development and the same data policy, offering a perfect image source for long term surface monitoring

([https://sentinel.esa.int/documents/247904/349449/S1\\_SP-1322\\_1.pdf](https://sentinel.esa.int/documents/247904/349449/S1_SP-1322_1.pdf)). Due to its favorable properties, S1 quickly became a standard raw material for interferometric processing purposes in recent years.

Interferometric techniques are used to calculate and monitor permanent and temporary terrain displacements with remarkable precision. The three

main types of interferometric methods vary greatly and are used expansively in various applications. Basic interferometry (InSAR) uses two SAR images to create a digital elevation model. The more advanced method, differential interferometry (DInSAR) uses at least two images and other auxiliary input data i.e.: digital elevation model (DEM) to calculate sudden changes and deformations of the surface with centimeter precision (fig. 1) [1, 2]. This method, however, still carries some inaccuracy caused mainly by the topography and atmospheric noise (APS). For measuring slow, small-scale displacements, interferometric stacking methods have been developed. Using this technique, atmospheric noise can be eliminated, and measurements down to sub-millimeter precision are achievable [3, 4].

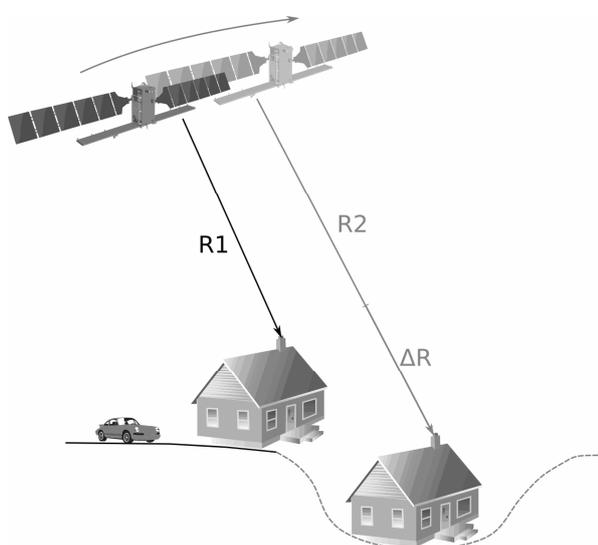


Fig. 1. Theoretical sketch of an interferometric measure

One of the most common, and in fact, the oldest stacking method is the Persistent Scatterers (PS) approach that is widely used for monitoring surface deformations in urban areas, and around anthropogenic structures. PS algorithm focuses on small objects with very distinct geometry and high temporal stability. The method requires the selection of one particular image from the input stack which is used as a master for calculating differential interferograms between this selected image, and all the other acquisitions [5].

The algorithm then focuses on point targets that are showing no considerable differences in backscatter amplitude throughout the time series, and more importantly having high values of temporal coherence, and choosing only them as PS points. Furthermore, the algorithm utilizes the phase time series of every pixel individually, without performing any phase unwrapping and additional filtering to preserve the original spatial resolution of the image

stack. The results of the process can be visualized as a vector map of the PS points, and the associated database containing the registered movements of every point individually. The most important attribute is the average linear displacement rate (mm/year), alongside other qualitative indicators, such as velocity precision, height precision, coherence, and displacements according to dates [6].

In general, any construction above the ground that is able to provide sufficient scatterers, and has a favorable geometry aligning well with the sensor is observable with this method to some point. However, the achievable accuracy varies greatly according to the sensor's capabilities (e.g. wavelength), the temporal separation of the acquisitions, and the number of the processed images. Utilizing the full potential of the interferometric stacking technique, it is capable of monitoring a wide range of building deformations in general, from individual free-standing buildings (water towers, churches) to industrial areas, city districts, up to as large scale as regional/national level monitoring [7]. Particularly favorable application is the reliable and continuous monitoring of critical infrastructures, such as nuclear reactors and other power plants, chemical facilities, dams and water reservoirs, bridges, health, education, and research facilities, track-based transportation, e.g. [8-14].

Apart from infrastructure, surface movements are also traceable, regardless of the root cause - undermined areas, city districts and individual structures above underground constructions, or areas affected by mass movements (falls, slides, avalanches) [15-18]. Landfills and open-pit mines after recultivation are also prone to instability and movements, therefore any structures built atop such a surface are also might be subject to some level of displacement.

For utilizing interferometric stacking methods, it is necessary to calculate with certain limitations of the image-producing sensor and the algorithm of choice. The PS algorithm works with a linear displacement model, which practically means that rapid changes in the movement rates or directions usually remain partially hidden. On the other hand, image stacks with short temporal baselines (S1) can overcome this limitation. The PS technique is based on coherent measurements, and as such, dependent on the coherence of the object. PS points are geometrically well-characterized, reflective surfaces, with long-term phase stability. Therefore, the detection of extensive flat surfaces and not very well characterized objects (i.e. highways, airport runways) is solvable with other dedicated algorithms like Small-BASeline Subsets (SBAS) [19].

Noticeably, when working with Sentinel-1 images, the surface movement occurring in line with the sensor's orbital plane mostly remains hidden, hence, only non-parallel components of displacements will be well detectable. Compared to other sensors, assigning the exact geolocation to the detected PS points is less accurate using Sentinel-1, due to the short baseline of the sensor. This shortcoming also can be improved to some degree by utilizing the most precise digital elevation model available. Considering all these factors, S1 images are better performers on large scale, long-time monitoring of structures. However, with careful evaluation, individual smaller structures are also monitorable. Although some other image-producing platforms operate with higher spatial resolution, none of those has free availability or 6 days revisit times. Even with some slight limitations to tackle, combining its qualities, the S1 is indeed an adequate platform to work with on infrastructure monitoring due to its uniquely frequent revisit time, freely available imagery, adequate sensor design and the predicted long lifetime of the mission. For the most comprehensive result, it is advisable to combine the relevant tools of structural monitoring, traditional ground measurements and in-situ sensors with the capabilities of the PS technique.

#### **Case study on a reinforced concrete water tower**

##### *Tests and analyses for structural assessment*

Our task was to carry out an overall structural assessment of the Rókus water tower in Szeged, Hungary. The design of the tower started in 1977 and the construction was finished in 1985. The 66.5m high reinforced concrete structure has two water tanks with a 4000m<sup>3</sup> full storage capacity. The static analysis aimed to confirm the load-carrying capacity, serviceability, durability, and stability of the structure. As the original design was

unavailable, all input parameters for the analyses had to be determined by testing procedures. These include visual inspections, 3D geometrical measurements and various non-destructive test methods together with local chemical tests on drill powders.

The structural stability was previously confirmed by periodical geodetic measurements in 10 years long periods, where the displacements of the tower at selected points were determined each time and compared with the preceding values. Based on the available accuracy of the conventional geodetic method the measured horizontal displacements at the top section were within the range of 30-60 mm showing remarkable variability. However, no vertical displacements were measured during the periodic investigations.

The Axis VM Finite Element software package was used for the numerical analysis of the structure, based on the measured structural and material parameters. Durability parameters and extreme local variations of the properties were incorporated into the model. The numerical model allowed the analysis of forces, stresses and displacements of the structure subjected to loadings related to normal use, temperature variations, ground settlements, environmental and seismic effects. The structural assessment was made according to the EN standards.

The displacement results were calculated at selected points of the structure by assuming the measured or most likely values for the effects like seasonal temperature variations, loads from filling and emptying the water containers, wind forces, etc. Variations and ranges of these modelled displacement values were compared with the relevant components of the measured displacements based on the InSAR monitoring (see point 2.2). Table 1 and Table 2 summarize the steps of the assessment and the test methods used for each assessment step.

**Table 1. Overview of the applied assessment steps and methods**

Assessment step	Methods used	Results
STEP 1: Condition review	Normal visual inspection. Photo documentation. Portable microscope. Inspection with alpine technique	Damage map. Damage evolution assessment. Condition rating
STEP 2: 3D geometrical measurement	3D laser scanning. Drone-photogrammetry. Tapes	3D point cloud. Models of structural elements (external). 3D CAD model
STEP 3: Non-destructive testing	Magnetic rebar locator. Georadar (450-2000 MHz). Rebound hammer. Ultrasonic tester. Chemical tests on drill powder. Crack microscope.	Materials and models of structural elements (internal). Rebar configurations. Structural layers. Material strength parameters. Material durability parameters

Table 1 (continued)

Assessment step	Methods used	Results
	Resistivity meter. Videoendoscope	
STEP 4: Structural analysis	Finite-element modelling (static, dynamic)	Structural behaviour under static and seismic loading. Static assessment (structure, foundation). Seismic assessment
	Probabilistic analysis	Reliability of durability
STEP 5: Stability monitoring	InSAR (Interferometric Synthetic Aperture Radar), Periodic geodetic measure- ments	Time-series information on global structural stability
STEP 6: ASSESSMENT	Evaluation of structural condition (load-carrying capacity, serviceability, durability, stability)	

Table 2. Assessment steps 1-5

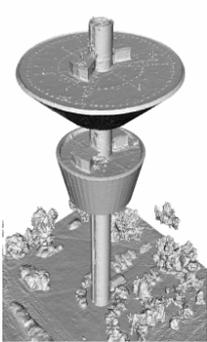
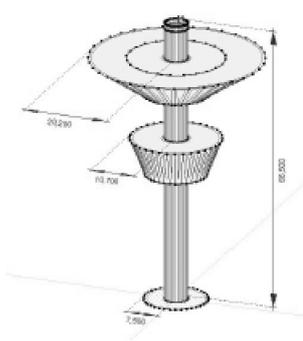
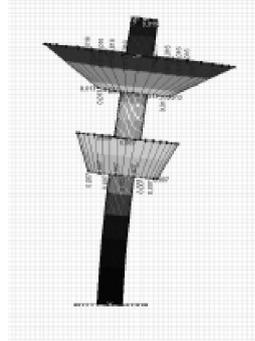
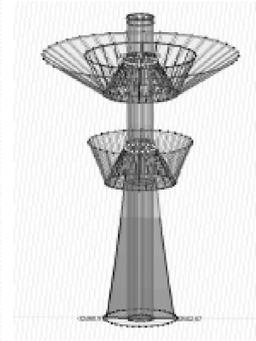
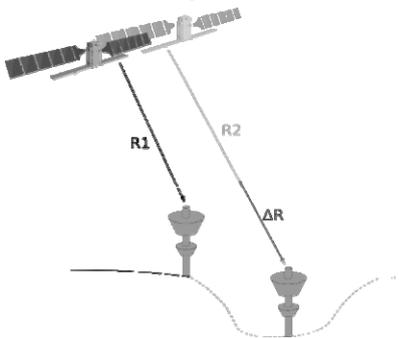
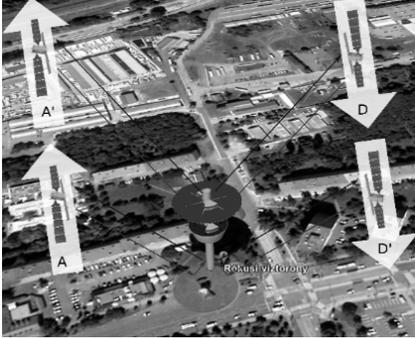
STEP 1: Condition review by normal visual inspection and alpine technique		
		
STEP 2: 3D geometrical measurement by drone photogrammetry and laser scanning		
		
STEP 3: Non-destructive testing of structural and material characteristics		
		

Table 2 (continued)

STEP 4: CAD modelling of geometry and FEM modelling of structural behaviour			
			
STEP 5: Stability monitoring with InSAR			
			

#### Displacement monitoring with InSAR

For investigating the stability of the water tower with the PS interferometric technique all available Sentinel 1 imagery in both geometries were used. 273 images between 29/10/2014 and 27/09/2020 in ascending geometry (orbit 175) and 281 images between 21/10/2014 and 01/10/2020 in descending geometry (orbit 51) were processed separately according to geometries. The temporal spacing of the imagers was 12 days before October of 2016 and image acquisitions became more frequent afterwards with 6 days of temporal image separation. Images were downloaded from the Alaska Space Facility's Vertex server (<https://search.asf.alaska.edu/#/>) as single look complex (SLC) files. For the interferometric and geocoding step of image processing, the SRTM digital elevation model (DEM) 3 (ver.4) was used and it was downloaded from the [srtm.csi.cgiar.org](http://srtm.csi.cgiar.org) webpage.

As the first step of PS processing, images were imported to the SARscape 5.5.4. module of ENVI 5.5, where satellite orbit data was applied on them. Secondly, the processing area was delineated, and images were sample selected to a limited area to reduce processing time. PS processing started with the creation of a connection graph where master and slave images (composing image stacks according to geometries) were automatically selected. Images were first coregistered then the stacks were

used for creating differential interferograms (between master and slaves). These interferograms were further analysed in order to find PS points in the 'First inversion' step. Moreover, a linear model of displacement was established in case of all detected points. Atmospheric modelling and noise removal were done in the upcoming 'Second inversion' step using low and high pass filters. As the last processing step, geocoding of the data was done evaluating the SRTM 3 DEM. The outcome of the whole procedure was a vector file of the PS scatterers, which contained the PS locations and adjacent descriptive parameters, such as the average velocity of point displacements (mm/y), displacements according to dates, coherence, estimated height, velocity precision, height precision and geographic location of PSs.

Using the above-mentioned PS technique, the periodical displacements of the water tower, in terms of the line of sight (LOS) values at selected points were measurable. Four PS points were identified in ascending, while six PSs were detected in descending geometry on the tower. The temporal evolution of all the points reflected clear temporal stability with  $\pm 15$  mm fluctuations between 2014 and 2020 considering the LOS displacement values. Vertical (figure 2) and east-west displacements were also extracted combining both the geometries and displacements also reflected the stability of the tower.

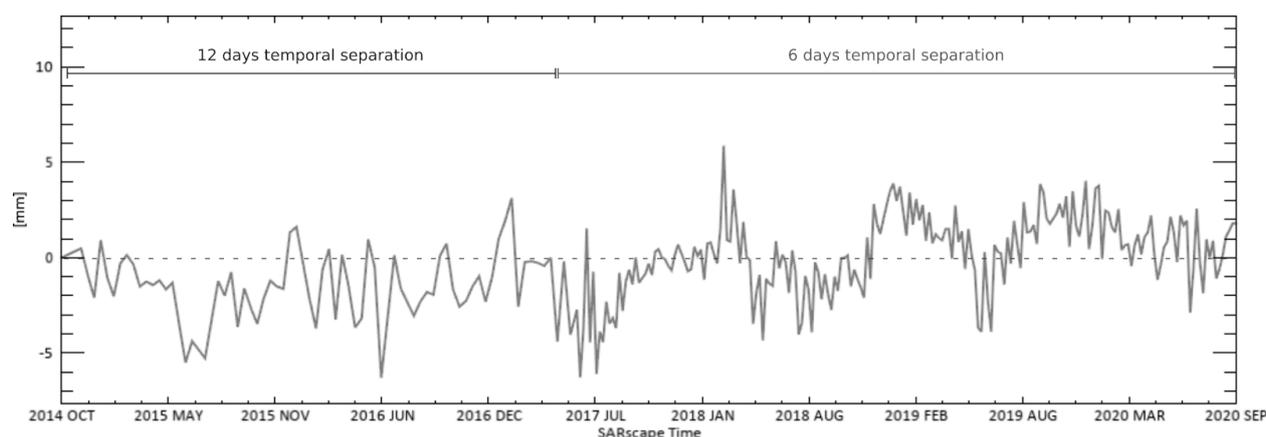


Fig. 2. Vertical InSAR measurement of the water tower by Sentinel-1

The InSAR monitoring data series confirmed that the displacement of the structure from an ideal, original position has only seasonal variations, there is no tendency for canting or subsidence.

### Conclusions

Based on the results of the applied non-destructive testing, numerical analysis and InSAR monitoring the following conclusions can be drawn.

The point cloud-based 3D geometrical measurements together with NDT tests provided data with sufficient accuracy for the numerical structural analysis. The obtained data set included both geometrical and mechanical parameters of the structural materials and elements.

Based on the numerical analyses the carrying capacity of the structure was assessed and the structural behaviour was analysed. Material parameters based on durability tests were taken into account in the assessment, where the relatively large number of data allowed a probabilistic reliability analysis on the main load-bearing elements of the structure. The analysis confirmed sufficient structural reliability and helped describe the structural behaviour under various loading scenarios.

Variations and ranges of the displacement values derived on the numerical model were comparable and showed a good fit with the relevant components of the measured displacements based on the InSAR monitoring. The temporal evolution of all points reflected clear temporal stability with  $\pm 15$  mm fluctuations between 2014 and 2020 considering the LOS displacement values obtained by InSAR monitoring.

The displacement values (fluctuating between 0...1.1 mm/year) of the top section of the tower derived from the InSAR monitoring indicated variations both in horizontal and vertical directions. These variations suggest changes in parameters at-

tributed to seasonal periodicity and deformations during the normal usage of the structure.

The accuracy and variability of the conventional geodetic measurements were confirmed by the InSAR monitoring data. The precision of the InSAR velocity data (phase processing accuracy) varied between 0.05 and 0.01 mm/year which reflects the high quality of the InSAR measurements.

It has been shown that InSAR techniques can be effectively applied to the stability monitoring of the tower, however, the exact interpretation of the temporal variations of the structure requires further investigations. Basically, the decomposition of the environmental contributors in the signal measurement is a complex task. Even though the environmental contributors are not separated from the signal, it shows fluctuations in a similar range ( $\pm 15$  mm) obtained by the numerical structural model. This connection is not identical between the different measurements, but it serves as a promising basis for a future multidimensional data fusion.

It is highlighted that the interpretation of InSAR monitoring data can effectively be assisted by numerical modelling of the structural behaviour. It is especially important in the case of vertical structures where effects from normal usage and environmental impacts can cause considerable deformations.

Sentinel-1 InSAR processing was already supported structural displacement assessment. However, if higher spatial resolution commercial data is available (TerraSAR-X, COSMO-SkyMed) over the targeted structure, it could provide further details of deformation in comparison to traditional survey techniques.

### References

1. Hein A. Processing of SAR data. Fundamentals, signal processing, interferometry. Springer, Berlin, 2004. ISBN: 978-3-662-09457-0.

2. Karpes B.M. Radar Interferometry - Persistent Scatterer Technique. Springer, 2006. ISBN: 978-1-4020-4723-7.
3. Ferretti A., Prati C., Rocca F. Permanent scatterers in SAR interferometry. IEEE Transactions on Geoscience and Remote Sensing, 2001, 39, 8-20.
4. Monti Guarnieri, A., Tebaldini, S. Hybrid Cramér-Rao bounds for crustal displacement field estimators in SAR Interferometry. IEEE Signal Processing, 2007, Letters 14 (12), 1012-1015.
5. Ferretti A. Satellite InSAR data: Reservoir monitoring from space. EAGE Publications, The Netherlands, 2014. ISBN: 978-90-73834-71-2.
6. Pasquali P., Cantone A., Riccardi P., Defilippi M., Ogushi F., Gagliano S., & Tamura M. Mapping of ground deformations with interferometric stacking techniques. In: Holecz F., Pasquali P., Milisavljevic N. (eds.). Land applications of radar remote sensing, 2014, 234-259. Intech. DOI: 10.5772/55833.
7. Bakon M., Papco J., Perissin D., Sousa J., Lazecky M. Multi-sensor InSAR deformation monitoring over urban area of Bratislava, Slovakia. Proc. Computer Science, 2016, 100, 1127-1134. <https://doi.org/10.1016/j.procs.2016.09.265>
8. Perissin D., Wang Z., Lin H. Shanghai subway tunnels and highways monitoring through Cosmo-SkyMed Persistent Scatterers. ISPRS J. of Photogrammetry and Remote Sensing, 2012, 73, 58-67.
9. Mazzanti, P., Perissin, D., & Rocca, A. Structural Health Monitoring of Dams by Advanced Satellite SAR Interferometry: Investigation of Past Processes and Future Monitoring Perspectives - tructural Health Monitoring of Intelligent Infrastructure. 7<sup>th</sup> International Conference (1-3 July 2015). Torino, Italy, 2015.
10. Heimlich C., Gourmelen N., Masson F., Schmittbuhl J., Sang-Wan K., & Azzola J. Uplift around the geothermal power plant of Landau (Germany) as observed by InSAR monitoring. Geothermal Energy, 2015, 3, 2. <https://doi.org/10.1186/s40517-014-0024-y>
11. Selvakumarana, S., Plank, S., Geiss, C., Rossi, C., Middleton C. Remote monitoring to predict bridge scour failure using Interferometric Synthetic Aperture Radar (InSAR) stacking techniques. International J. of Applied Earth Observation and Geoinformation, 2018, 73, 463-470.
12. Milillo P., Bürgmann R., Lundgren P., Salzer J., Perissin D., Fielding E., Biondi F., & Milillo G. Space geodetic monitoring of engineered structures: The ongoing destabilization of the Mosul dam, Iraq. Scientific Reports, 2016, 6, 37408. <https://doi.org/10.1038/srep37408>.
13. Milillo P., Giardina G., Perissin D., Milillo G., Coletta A., Terranova C. Pre-Collapse Space Geodetic Observations of Critical Infrastructure: The Morandi Bridge, Genoa, Italy. Remote Sensing, 2019, 11, 1403. doi:10.3390/rs11121403.
14. Wang Q., Zhao Q., Ding J., Fedotov A., Badenko V., Liu M., Pepe A. Investigation of the ground displacement in Saint Petersburg, Russia, using multiple-track differential synthetic aperture radar interferometry. International J. of Applied Earth Observation and Geoinformation, 2020, 87. <https://doi.org/10.1016/j.jag.2020.102050>
15. Colesanti C., Ferretti A., Prati C. and Rocca, F. Monitoring landslides and tectonic motions with the Permanent Scatterers Technique. Engineering Geology, 2003, 68, 3-14.
16. Colesanti C., Le Mouelic S., Bennani M., Raucoules D., Carnec C., Ferretti A. Detection of mining-related ground instabilities using the Permanent Scatterers technique - a case study in the east of France. International J. of Remote Sensing, 2007, 6, 201-207. <https://doi.org/10.1080/0143116042000274069>.
17. Anderssohn J., Steinacker A. Satellite-supported measurement of ground motion for the recording and monitoring of elevations in the urban area of Boblingen - Satellitengestützte Bodenbewegungsmessung zur Erfassung und Überwachung von Hebungen im Stadtgebiet von Boblingen. GIS Business, 2019, 12, 50-51. <https://doi.org/10.26643/gis.v12i3.5192>.
18. Hu B., Chen J., Zhang X. Monitoring the Land Subsidence Area in a Coastal Urban Area with InSAR and GNSS. Sensors, 2019, 19, 3181. <https://doi.org/10.3390/s19143181>.
19. Berardino P., Fornaro G., Lanari R., & Sansosti E. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. IEEE Transactions on Geoscience and Remote Sensing, 2002, 40, 2375-2383.

## Интеграция технологии InSAR в оценке устойчивости конструкций

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*Неразрушающий контроль зданий и сооружений является актуальной проблемой в современном строительстве. Несмотря на то, что за последние десятилетия было разработано много измерительных методов, все же остаются некоторые пробелы в системе оценки состояния зданий и сооружений. Одна из основных проблем заключается в том, что измеряемые параметры оцениваются лишь время от времени. Существует ограниченное количество доступных методов, которые могут обеспечить непрерывный мониторинг технического состояния строительных сооружений и предоставить информацию об их устойчивости во*

временном ряду. Основная цель данной статьи – представить диагностический метод, который может преодолеть упомянутые недостатки, сочетая периодические неразрушающие измерения с непрерывным мониторингом, получаемым путем применения спутникового дистанционного зондирования. Радар с синтезированной апертурой (SAR) имеет много преимуществ, которые стоит учитывать инженерам-строителям в практике оценки устойчивости зданий и сооружений. Наша задача – дать представление о теории интерферометрических радаров с синтезированной апертурой (InSAR) и продемонстрировать их совместное применение с другими методами оценки состояния зданий на конкретных примерах.

Эффективность предложенной методики была продемонстрирована сравнением результатов смещения водонапорной башни, полученных с помощью мониторинга InSAR, традиционной геодезической съемки и численного анализа.

**Ключевые слова:** гражданское строительство, структурный мониторинг, InSAR, Sentinel-1, неразрушающий контроль.

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