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An overview of ground surface displacements generated by groundwater dynamics, revealed by InSAR techniques

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Abstract

One of the main activities causing subsidence in the urban environment is the dynamics of groundwater due to abstraction and recharge as well as its interaction with subsurface infrastructure systems. For a sustainable spatial planning, the complexity of urban environment demands the utilisation of new methods for monitoring and quantifying the effects of the underground processes. One of the remote sensing methods developed in the last decades, offering the opportunity for early detection of land subsidence in urban areas is the interferometric synthetic aperture radar (InSAR). By its different techniques, this method started to be used in correlation with several underground and ground measurements for revealing diverse parameters characterizing the dynamics of groundwater, including seasonal and long-term aquifer-system response. Considering both groundwater and underground structures, an overview of several studies realised in different sites, based on InSAR techniques, is presented.

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1. Introduction

Natural environment, substantially altered by human activities, can lead to different ground surface degradation forms (e.g. landslides, land subsidence, differential settlements). As urban population is in a continuous growing

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process, any land surface degradation form can substantially affect the inhabitant's life. One of the main activities causing subsidence in the urban environment is the dynamic of groundwater due to abstraction and recharge as well as its interaction with subsurface infrastructure. In this category the use of groundwater for water-supply and industrial purposes, pumping of large volumes of groundwater for the construction, maintenance of underground infrastructures, and many others can be included.

For a sustainable spatial planning of the urban environment [1], new methods for monitoring and quantifying the effects of the underground processes should be utilized [2]. In the last decades, remote sensing by its qualitative and quantitative acquisitions performed repetitively and with a large spatial coverage, offered the opportunity for early detection of land subsidence in urban areas. Synthetic Aperture Radar (SAR) techniques are especially used considering their detection and estimation capabilities of land degradation phenomena [3]. By correlation with groundwater level or with other ground measurements [4,5], time-series SAR Interferometry data started to be used for revealing different parameters characterizing the dynamics of groundwater (e.g. seasonal and long-term aquifer-system response, flow properties, groundwater barriers identification) [4,6].

2. SAR Interferometry techniques

2.1. InSAR technique

Synthetic Aperture Radar (SAR) sensors are active sensors using as illuminating source the microwave energy, which have cloud-penetrating capabilities and allow the data acquisition both day and night [7,8]. Information provided by SAR systems, which are coherent systems, is recorded both in the amplitude and phase of the backscattered echoes. This methodology consists on generation of an interferometric pair using two radar scenes which are acquired approximately from the same look angle [9] and over the same area, at different times [4]. In radar interferometry the first image from the interferometric pair is named the master scene and the second is the slave scene [10]. The SAR interferogram is generated by multiplying the first SAR image with the complex conjugate of the second one [8]. The interferometric phase represents the phase difference between the images, while the interferogram amplitude is the amplitude of the first image multiplied with the amplitude of the second one [8]. Their phase difference represents the interferometric fringes which can be used for generating Digital Elevation Models (DEM) [9]. The interferometric phase ($\Delta\varphi$) can be written as a sum of the following parameters:

$$\Delta\varphi = \frac{4\pi}{\lambda}\Delta R + \alpha + t + noise \tag{1}$$

where ΔR is the range displacement of the radar target, α is the atmospheric effect, t is the topographic distortion arising from slightly different viewing; *noise*- it has as one of the contributing factors the decorrelation effects [11]. As it was specified previously, a SAR interferogram can be used for generating a DEM, but the presence of the topographic distortion and of the atmospheric effect does not allow the estimation of surface deformation [11].

A number of limitations of SAR Interferometry (InSAR) techniques are: the decorrelation of land surfaces covered with vegetation, incoherence caused by large satellite orbit separations between the two acquisitions (also referred to as the baseline), long time period between two acquisitions, system noise, and radar penetration through the scattering medium [3,10,12]. The monitoring area is coherent if surface characteristics remain unchanged in both images [3].

2.2. DInSAR technique

Based on InSAR principles, SAR Differential Interferometry (DInSAR) represents a technique for which more pairs of SAR scenes acquired with the same geometry (or a SAR interferogram and a DEM) are used in order to remove various factors such as the topographic contribution or the atmospheric effect from the interferometric phase [2,8,11]. The removal of these factors allows the generation of a deformation map for the coherent areas, the differential interferometric phase being in a simplified form written as:

$$\Delta\varphi = \frac{4\pi}{\lambda}\Delta R + \alpha \tag{2}$$

where ΔR is the range displacement of the radar target and α is the atmospheric effect.

As the atmospheric effect is still present in the differential interferometric phase, DInSAR is not feasible for accurate displacement measurements, but it can be used for measuring total displacement between two points [11].

2.3. PSInSAR technique

In order to estimate and correct residual atmospheric phase, DEM errors and sub-pixel target position related phase offsets, new InSAR techniques were developed, the most accurate being the Persistent Scatterer SAR Interferometry (PSInSAR) [2]. The main difference of this technique from the previous ones is the development of multiple SAR interferograms, minimum 12 SAR scenes according to [2], minimum 15 according to [11] and more than 30 according to [6], in order to identify a network of persistent scatterers [6], in order to develop displacement time series [4]. A permanent scatterer is defined as a temporally stable, highly reflective ground feature [6], a radar target within a resolution cell, displaying stable amplitude properties and coherent signal phase throughout all SAR scenes [11]. One of the particularities of this method is that all datasets are registered to a unique master scene [2].

PSInSAR measurements are made in the line-of sight (LOS) and are relative to a point that is preselected as being stable and not-moving. The velocity map will be obtained by sequentially calculating the relative displacement between an individual radar target and the reference point, during all analysis period [11].

Some of the advantages of this method are: the removal of atmospheric phase contributions, the use of all available radar data regardless the geometrical baseline, achievement of good phase coherence using the available data [4], accuracy of milimetric level [2].

3. Land subsidence areas

Land subsidence is a world-wide spread problem having different anthropogenic or natural causes like the aquifer-system compaction (e.g. Mexico City), dewatering of organic soils (e.g. Dutch landscape), underground mining, hydrocompaction, natural compaction, sinkholes, thawing permafrost [13,14]. In the U.S.A, in 1991 it was reported that more than 80% of the affected areas by land subsidence (more than 44 000 km^2) have as main cause the exploitation of groundwater[13].

Global Navigation Satellite System (GNSS) and leveling networks are deformation monitoring methods commonly used for geomorphology and hydrology purposes. The InSAR techniques were first utilized for the study of earthquakes, volcanic activity and land subsidence produced by mining activities before being adopted in the analyses of the geomorphology and hydrology purposes [15]. There were situations when results of InSAR investigations revealing subsidence were assigned to groundwater dynamics but without a comprehensive hydrogeologic interpretation of the results [6]. The studies carried on in the last two decades show the advantages of complementing the existing in-situ measurement methods with the InSAR data.

Related to water pumping in urban area, significant InSAR land subsidence case studies were analyzed world-wide, including also several regions of Europe, using different SAR data.

3.1. Antelope Valley case study

One of the first areas where InSAR technique was used to detect and map aquifer-system compaction was Antelope Valley, Mojave Desert, California. Antelope Valley is situated about 80 km northeast of Los Angeles, one of the main cities from this area being Lancaster. Until 1980s the groundwater destination was agricultural irrigation, since then the increasing population number changed its utilization to urban needs [16,17]. This region is characterized by basin fill sediments establishing a large groundwater basin, overlying three wide structural basins which contains to depths of more than 1.5 km Tertiary and Quaternary alluvial sediments. The groundwater basin is conceptually separated in 12 subbasins, Landcaster subbasin being the most developed. The vertical layers of this subbasin consist of transmissive aquifers interbedded with aquitards, the main aquifer systems being known locally as the "principal aquifer" and the "deep aquifer" [17].

The subsidence investigations in this area are heterogeneous, some of the historical data being available from 1930, namely differential-leveling. Other subsidence investigations include GPS survey and extensometer measurements. The extensometer measurements in the Antelope Valley area were achieved at two borehole locations, one of them being Holly borehole site (established in 1990 and anchored 256 m underground), and Lancaster borehole site (established in 1996 and anchored at 363 m depth) [6,16].

A first correlation between historical subsidence data from 1930 to 1992 and InSAR subsidence detected using an interferogram pair for the period 20 October 1993 to 22 December 1995 was made by Galloway et. al in [113]. The used SAR data was achieved by the European ERS-1 satellite mission. By overlapping the contour of the historical land subsidence on the in InSAR subsidence map it could be revealed that the historical subsidence pattern was kept in the InSAR map [17]. Using the data registered at the Holly site borehole extensometer, a comparison between the InSAR detected subsidence and the aquifer-system compaction revealed by the extensometer was realized. Therefore, the InSAR highlighted at that site a subsidence value of 40 mm and the extensometer a value of 31 mm. The geodetic survey made at the same site revealed also a subsidence rate of about 1.5 times the extensometer compaction, the InSAR results being in line with the geodetic ones. The difference between the extensometer and the other measuring means were attributed to the compaction bellow the extensometer anchor (256 m) [6,17]. Considering the Lancaster groundwater subbasin, a simulated land subsidence and groundwater flow model was used to evaluate the InSAR subsidence, using as model constrains the available water pumping data and the aquifer system compaction data. The InSAR subsidence was mostly consistent with the simulated model, the results revealing the possibility of using InSAR to better constrain land subsidence models [6,17,18]. Beside the interferometric data for the 1993-1995 period, other 22 interferograms for the period 26 January 1996 to 1 May 1999 were used for compaction comparison with the borehole extensometer data from Holly site and Lancaster site and the results highlighted a good agreement between these different data [6].

Similar studies were conducted in many U.S. sites, including Las Vegas Valley- Nevada, Santa Clara Valley- California, Los Angeles-California as mentioned by [6,18].

3.2. San Luis Valley, Colorado

A most recent study considering a confined aquifer and its particularities was made in the San Luis Valley, Colorado[5]. This area is located in the southern-central part of Colorado state, near the border with Mexico City. It can be divided in four different regions: the Closed Basin (the half Northern part of the valley), the Conejos and Alamosa River Valleys (in the South-Western part of the valley), San Luis Hills (the south central part) and the Costilla County (the south eastern part of the valley). The area has as top layer an upper unconfined aquifer (15-40 m depth) (layer 1), with an aquitard underlayer (layer 2), the next three layers representing the confined aquifer system. Rio Grande Water Conservation District Confined Well list offered the data for the 37 confined aquifer wells from the region. Because of the inconsistence of the data of some wells for the joint InSAR-well data analysis, only 24 wells were used in the analysis [5].

The InSAR data analyses was based on L-band ALOS PALSAR scenes acquired in the period 6 January 2007 and 4 March 2011, 63 interferograms being generated. During the SAR scenes processing, after a reference point with no deformation was chosen, the InSAR Line-of-Sight (LOS) deformation was converted to vertical deformation. Considering this step, the first analyses were made using two interferograms, one for the period 16 April 2010-1 September 2010 and the other for the period 1 September 2010-4 March 2011. An InSAR summer subsidence of 7.1 cm and a winter uplift of 7.2 cm were determined and compared with the head change measured in the same periods for one of the wells. It could be revealed a temporal and spatial correlation between the InSAR and hydraulic head measurements. The long term subsidence for the period January 2007 to March 2011 and correlated with the hydraulic head measurement at the same well showed a maximum multi-annual subsidence lower than 1 cm. Considering the analyses made for all 24 wells it was concluded that the InSAR observed deformation was elastic. An interesting result of the study was that the InSAR head assessment is compatible with the well data, hydraulic head could be refined for periods when well data was missing using the InSAR head estimation [5].

3.3. Ottignies-Wavre, Belgium

One of the European sites where a subsidence process has been detected using PSInSAR techniques is the Ottignies-Wavre area, Belgium [7]. This site is situated in the south-eastern part of Brussels and it is included in the hydrological basin of the Dyle River. The differential SAR analyses were made using ERS 1 and 2 data sets for the period 1992-2003, considering seventy-four scenes with 173000 permanent scatterers for the time-series analyses. The area has four aquifers from which water is extracted. The upper aquifer is the Quaternary sediments alluvial aquifer. It is followed by the sands of Brussel Formation and by the Cretaceous sediments. The lowest aquifer is the fissured Cambrian rocks (divided in two aquifers) [7].

The PSInSAR technique applied for the ERS data revealed a displacement map with annual subsidence values between -1.3 and -4.7 mm in the urban Ottignies-Wavre area. By overlaying the map with the well water catchments location on the PSInSAR subsidence map, it has been highlighted that many of the water catchments with large volume of extracted water are located in the subsidence area. Another important aspect in the subsidence results interpretation is that the urban area was established on alluvial sediments which can lead to compaction processes and have a part in the displacement process [7].

3.4. European initiatives for urban subsidence monitoring: Terrafirma and PanGEO

As ground motion is an important phenomena considering its consequences, there are two initiatives at European level providing ground motion hazard information service.

Terrafirma is a service which was supported by the European Space Agency’s (ESA) Global Monitoring for Environment and Security (GMES), the current Copernicus service programme. It was started in 2003 and Ground Motion was estimated using PSInSAR techniques applied to more than 50 radar scenes from an archive dating back to 1991. The initial services were focused on urban subsidence and landslides from different European countries, including also an interpretation of their main triggers. The results of this analysis made for 14 cities across Europe can be found in an Atlas. During more than 10 year this service provided diverse products considering themes as hydrogeology, tectonics, coastal lowland subsidence and flood defense [19].

Another European initiative was PanGEO- Enabling Access to Geological Information in Support of GMES, a project funded under the Seventh Framework Programme (FP7) of European Commission. Using PSInSAR ground motion maps, PanGEO provided stability information for several large cities from Europe (more than 50 cities)[20]. The ground instability areas were named in the frame of this project “geohazards” areas. For all studied sites detailed analyses of local geological data combined with the satellite data were made. The PanGEO data can be freely accessed on the project’s webpage [21].

3.5. Düsseldorf, Germany

In many cases the groundwater pumping processes are associated with the construction and maintenance of underground infrastructures (e.g. tunneling, railway station construction), the subsidence phenomen being the combined result of these operations.

An example of a tunneling process, which was monitored using PSInSAR techniques, is located in Düsseldorf, Germany [22]. For the period April 2011 to December 2011 a tunnel boring machine (TBM) was used for the tunneling process. The SAR data sets exploited for computing the velocity map were composed by 20 TerraSAR-X scenes acquired in StripMap mode from 7 January 2011 to 31 October 2011. To avoid the damage of the buildings from tunneling area, compensation injections have been performed. It is supposed that the deformation evolution has been influenced by the deformation solution in some points close to the tunnel entrance. There an uplift was detected after the work started. The velocity map of PS points indicated subsidence values up to 10mm, in the studied area, which were consistent with the leveling measurements from the same area. By this work, Liu et al. proved in [22] the ability of PSI for detecting fine movements of surface in the urban area.

3.6. La Sagrera Railway Station study case, Barcelona, Spain

Another study offering a comparison between results of leveling vs. InSAR in the monitoring process of an underground construction was realized for La Sagrera railway station, Barcelona [23]. The study area is located on the Mediterranean coast in a plain having as underground structure Quaternary formations followed by Pliocene marls series and Paleozoic granite. For the InSAR processing from the total of twenty-two TerraSAR-X scenes acquired between 27 March 2013 and 20 October 2014, eleven scenes were used, starting with the beginning of 2014. Considering the acquisition geometry, the LOS deformation measurements were projected into vertical direction. The leveling surveys started on 5 March 2014 and consisted of 54 campaigns. The leveling results revealed different behavior patterns considering the ground infrastructures. Hence, three areas were highlighted:

- The southern part characterized by high buildings with two underground parking floors where the final pumping settlements were lower than 1mm
- The pedestrian central part with final pumping settlements of 2-4 mm, and
- The northern part characterized by a subsidence of 1-2 mm in the early stages of monitoring and an uplift at the end of the monitoring

All levelling results were affected by the fact that the levelling control points were inside the pumping area, the values being mitigated with a constant ranging from 1 to 3 mm. The central pedestrian area revealed the most accurate water pumping displacements. The evolution of the ground motion from the northern part was influenced by the reduction of the extracted volume of ground water from a permanent dewatering system present close to the border of the tunnelling area.

The InSAR measurements have values with approximately 5 mm higher than the levelling ones. Considering the adjustment of levelling settlements, the difference could be of only 2 mm. This discrepancy could be explained by taking into account that the levelling observation points are placed close to the ground on the buildings' facades and the InSAR points are located mainly on the top of the buildings.

Both techniques have strengths and limitations. The main conclusion is that to obtain better results these methods should be used together [23].

3.7. New Metro line 5 (M5), Bucharest, Romania

Under the project "Integrated service for urban subsidence phenomena based on space-borne interferometric synthetic aperture radar (InSAR) and hydrogeological-geotechnical hybrid modeling"-Syris financed by the European Space Agency, the Technical University of Civil Engineering Bucharest (Groundwater Engineering Research Center and Geotechnical Laboratory) and Terrasigna made a displacement monitoring during the tunneling works of the metro line (M5) in Bucharest. The subsidence has been monitored in the same time with hydrogeological, geotechnical parameters and InSAR data [2].

Bucharest is situated in a plain area and it is characterized by the existence of three main Quaternary aquifer units. The upper one is an unconfined aquifer unit composed by sands and gravels. It is followed by a medium depth sandy confined aquifer and by the deeper strata aquifer unit [24].

The analyses included InSAR and topographic survey for vertical displacement identification, hydraulic-head and inclinometric measurements achieved in some representative points. The tunneling works for both lines started in 25th of March 2014 and were finished in the 8th of May 2014. The dewatering works at one of the metro stations took place from the beginning of April 2014 until the beginning of June 2014. For the InSAR displacement map realization, 20 TerraSAR-X SLC scenes in Stripmap mode were acquired during the period March 2014-February 2015. The InSAR measurement was calibrated on the basis of corner reflectors situated in the study area. Even though both SAR and in-situ measurements were affected by different phenomena (e.g. thermal expansion, underground works, temporal decorrelation between SAR and in-situ measurements), it could be revealed that the SAR displacement trends showed a good fit with the in-situ leveling ones [2].

Based on the SAR images acquired during the tunneling works and on other TSX data acquired during the period July 2011-September 2014, a new linear space-time pattern analysis approach was proposed for assessing possible connections between land surface perturbations and tunneling works. For this purpose, samples intervals of 25, 50 and

100 m wide with buffers of 10, 20 and 50 m and minimal (MIN), average (AVG) and maximal (MAX) values of deformation and deformation rates were accomplished [2].

InSAR analyses were used also for a comparison between the groundwater level fluctuation and the land surface deformation time series for several test sites from Bucharest, using data for the time periods 2006-2010 and the 2011-2013. The comparison did not revealed a clear correlation between the two phenomena excepting one site where for the interval 2011-2013 the seasonal groundwater and temperature fluctuations could be observed with a slight temporal delay [2].

4. Discussion

Several study cases were presented in this paper. It can be revealed that InSAR techniques can be used for monitoring subsidence produced by groundwater dynamics both for large areas (such as Antelope Valley or San Luis Valley) and for metropolitan areas (Ottignes-Wavre or the European cities monitorised in the frame of Terrafirma and PanGEO projects) and also for punctual purposes (the underground infrastructures from Düsseldorf, Barcelona and Bucharest). The study cases cover analyses made for different hydrogeological environments, by using different SAR data, different InSAR methods, and in comparison with other in-situ deformation monitoring methods. SAR measurements encloses data starting with the first radar missions ERS-1 and ERS-2 and reaching up the acquisitions of the current SAR sensors (such as TerraSAR-X). These data allowed revealing deformations of milimetric and centrimetric level. The centimetric level deformation were detected for the large studied areas, were the pumping process occurred for a long period of time (several decades) and the available SAR data cover also a few years. The water pumping process in the case of underground constructions was only a temporary work, the SAR analysis being made for a shorter period (approximately one year).

In the case of confined aquifer, the seasonal variations could be revealed by the seasonal variations of the ground deformations, the analysis including SAR data, hydraulic head measurements and extensometer data. For the underground structures monitoring an important contribution for the analysis have the leveling measurements which can be used in correlation with the InSAR for the best study results.

5. Conclusions

Urban subsidence resulted from different processes involving groundwater is an encountered phenomena. It could be revealed that in the last two decades InSAR techniques brought new elements in the estimation and interpretation of groundwater specific parameters by investigating their effects on ground surface. As any ground motion determination method, InSAR has its own limitations. However, these techniques are still under a refinement process as new radar satellites were recently launched (e.g, European Sentinel 1 satellites) and new approaches proposed. It might be also stated that InSAR techniques can be used successfully for complementing the in-situ subsidence measurements methods like leveling. There are still many issues to clarify, but the improvement of the InSAR techniques and of the available related data can optimize future groundwater monitoring activity.

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