Identifying linearity/non-linearity in landscape evolution by integrating satellite-based radar interferometry and ground-based monitoring data. Study area: Bucharest

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Abstract
This research project aims to identify landscape evolution trends in Bucharest based on high-resolution interferometric ground displacement products, using single and dual-polarimetric satellite data. The results based on multitemporal InSAR methodologies (initially applied to ERS, ENVISAT satellite data and later refined using TerraSAR-X/TanDEM-X satellite data), validated by ground-based monitoring data and conventional geological and geomorphological methods will capture the space-time evolution of the city. The understanding of these phenomena have long term theoretical and practical results in the context of climate change, offering the support to successful risk mitigation actions in urban areas. The outcome of the project will include validated interferometric-based ground displacement products in urban areas and a more effective process of interpretation of complex dynamics based on a holistic approach achieved by a multidisciplinary team of scientists and engineers.

Keywords
Change detection, PS-InSAR, GNSS, Validation, Levelling, evolution patterns

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1. Introduction

The newest generation of X-band satellites (TerraSAR-X or TSX, and TanDEM-X or TDX), launched in 2007 and 2010 by the German Space Agency or DLR, have dual-polarized sensors on board. Their satellite data significantly improves the level of detail of SAR-based analyses and extends the applicability of space-borne SAR interferometry to faster ground movements (and therefore a more comprehensive and better understanding of different landscape dynamics). Higher performances are achievable due to higher spatial resolutions (up to 1 m), and shorter repeat cycles (i.e., 11 days) with respect to the medium resolution SAR sensors, such as ENVISAT.
Initially the InSAR technique was used mainly for topographic mapping [13, 16, 35]. After 1989, the technique started being used in another type of application, which detects changes in the ground surface by removing the topographic component from the radar phase signal [14].
The range of applications is wide, varying from tectonics [20, 29], earthquakes [21], volcanoes [26]; uplifts and subsidence [15, 19, 24] to land use – monitoring [4, 32] and changes in land use [1, 10]. The technique is used also in risk studies, being applied in all situations from prevention to early response and risk mitigation. In these cases the applications include monitoring elements at risk and early response [11], damages after a risk occurred [5], for a whole range of risks, like landslides, earthquakes and landslides.
The assessment of instabilities in urban environments have also benefited from using the InSAR technique. Patterns of vertical movement have been identified at an international level [17, 19, 22, 34]. In Bucharest, the

conventional and radar interferometry techniques started being used only recently to detect and monitor changes [2, 23, 25] and for DEM extraction [9, 30].
In this project, assessment of recent ground deformations are focused on using multi-temporal InSAR techniques, aiming to highlight specific evolution types (linear/nonlinear), depending on the data availability. The interferometry techniques, based on high resolution radar satellite images, are very promising in providing the support technology for high precision ground displacements measurements, repeated periodically on extended surfaces. The project is coordinated by the University of Bucharest and was submitted in the STAR competition 2013, in the expertise domain Earth observation. It is based on the collaborative work of a multidisciplinary team of scientists and engineers from Romania and from abroad (USA, Portugal).

2. Objective and short description of the project

The **objective** of the project is to capture landscape evolution patterns in Bucharest within the context of the nonlinear dynamic system (NDS) theory, using single polarized synthetic aperture radar (SAR) satellite data and multi-temporal radar interferometry (InSAR) methodologies. Landscape evolution is generally nonlinear, being characterized by a number of typical phenomena discussed in detail by Phillips (2003). Applications of nonlinear and complex systems analysis (from stochastic and deterministic point of view) in the geosciences has been characterized as the natural importation of ideas and tools from mathematics, theoretical physics and chemistry, biology and computation. Terms such as chaos, fractals, self-organized criticality, turbulence and structural breaks are frequently used and seriously considered in earth surface systems [27, 28].
Unfortunately, the concept of deterministic chaos has remained in geosciences, specifically in geomorphology, more theoretical until now. There are no studies in NDS (nonlinear dynamical systems) theory applied to geomorphic systems based on precise spatial ground displacements measurements to support its evidence. There are also no spatial deterministic tools in geosciences to estimate the nonlinear invariants of spatial data. Our project will adapt/develop/implement spatial embedding methods for spatial data, which will allow us to estimate spatial Lyapunov exponents and other dynamics invariants which give us correct insights of chaotic and complex motion. Spatial embedding of nonlinear dynamical systems theory will also permit GIS integration and correlation of results with all environmental features of a specific place, creating an integrated model with a focus on simplicity, usability and efficiency.
To achieve this aim, working stages will focus on three important tasks (Fig. 1):
- The identification of instability areas using change analysis based on optical satellite data (i.e., Landsat imagery), diachronic cartography and historical radar satellite images (i.e., ERS-like and ENVISAT) and TSX/TDX data.
- Complex validation of radar displacement products based on Global Navigation Satellite System or GNSS, leveling geodetic measurements, as well as by conventional geological and geomorphological methods.
- Identifying linear/non-linear landscape evolution patterns in different spatial and temporal scales.

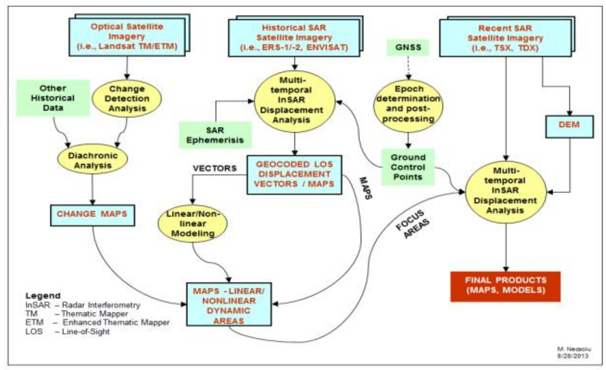

Fig. 1 The project structure in a chain of sub-goals

3. Preliminary results

The first task was focused on capturing the spatial evolution in historic time of the city (Fig. 2), based on historical maps and change analysis products using optical satellite data (i.e., Landsat imagery). The aim of the change analysis study using optical satellite data was to observe development characteristics of the urban area over a time period of 30 years.

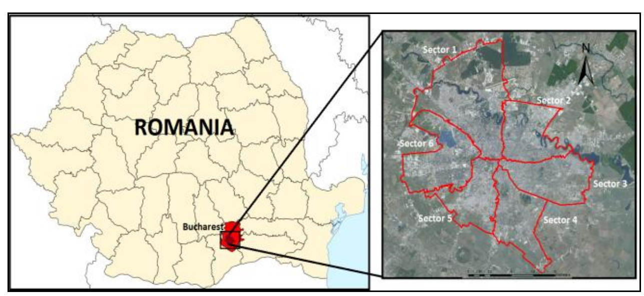

Fig. 2 Study area

In this purpose, Landsat (TM) and (ETM) data imagery in 4 differ bent years was used to monitor urban growth in Bucharest. The satellite images considered for the study describe the state of the land-cover in the city at the beginning and at the end of three important periods: 1980-1989, 1989-2000 and 2000-present. These time periods were chosen considering important political changes in Romania, which were likely to reflect the urbanization process of the capitol.

The satellite images were geo-referenced and then classified in four land-use classes: built-up area, water, barren lands and vegetated lands. The images were classified using a supported vector machine (SVM) classification. The SVM method was based on training algorithms of classification using user-defined training areas for each land-cover class. The classification results obtained using the SVM method showed an accuracy rate for classifying built-up areas of 97%. Applying the SVM algorithm allows a higher degree of automatization of the machine learning process. The change detection analysis was performed on the classified images considered as being of higher quality.

The process of multi-temporal change detection resulted in maps of change for each of the three periods (Fig. 3-6). The results of this process indicate major changes in the urban landscape that took place during each time interval. By looking at the new features that were built during each period, and to different fluctuations in the density of the built-up areas between years, we can conclude on how different political eras impact urban planning decisions. To identify (structural-) functional historical changes we employed a diachronic cartography method [31].

The principal development lines of the city from the perspective of the urban texture were identified based on a cartographic material (i.e., 1791, 1856, 1900, 1911, 1921, 1940, 1972, 1998, 2008), orthophotoimagery (i.e., 2006, 2007 and 2010 flights) which were later combined with products generated by analysis of high resolution optical and radar satellite images.

Specifically, maps of deformation based on radar interferometry using C- and X-bands were essential in quantifying the changes from recent years. Consequently we employed TanDEM-X data and InSAR, focusing on areas of maximum displacement identified in historical data.

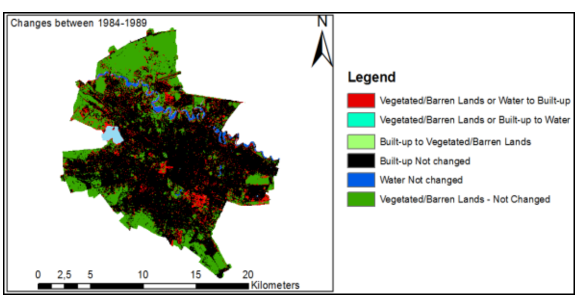

Fig. 3 Map of changes occured between 1984 and 1989

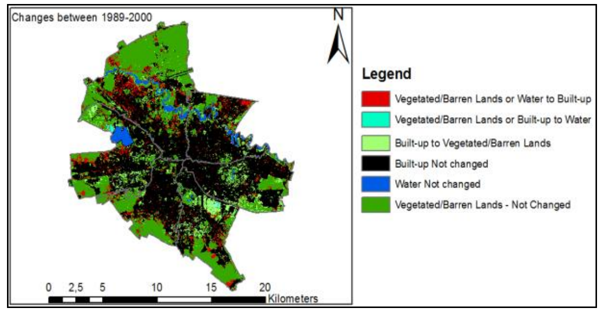

Fig. 4 Map of changes occured between 1989 and 2000

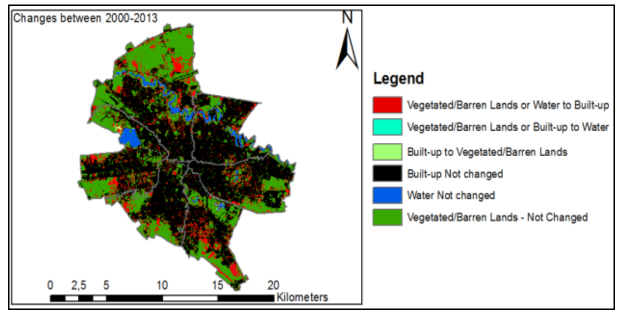

Fig. 5 Map of changes occured between 2000 and 2013

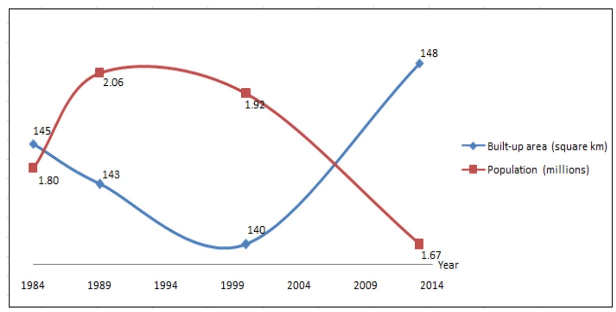

Fig. 6 Relationship between built-up area and population evolution over time

The second task aimed to complex validate radar displacement products over Bucharest based on Global Navigation Satellite System or GNSS, levelling geodetic measurements. There are few studies that compared radar-based estimations with geodetic measurements [6, 7, 8, 12, 18, 33]. Unfortunately, none of them were conducted in Romania or by Romanian scientists. GNSS (Global Navigation Satellite Systems) space technologies were used in Romania since 1992. An active development has taken place since 1999 when it was installed the first GPS permanent station at the Faculty of Geodesy, TUCEB, Bucharest, giving it a new importance to the tridimensional positioning technologies. GNSS determinations had a major application since the 2000s, when the national forum in the field, National Agency for Cadaster and Land Registration (NACLR) has established the national GNSS permanent network as a real support to the surveying activities in Romania. In Romania, GNSS satellite technologies are typically used for monitoring small localized targets. Studies and research have been made punctual (e.g., dams, landslides) without being used in conjunction with other methods (e.g., RADAR, LIDAR, etc.).

GNSS and InSAR give different results from a geometrical point of view: GNSS supplies the displacement vectors in three dimensions (X,Y,Z), while InSAR gives the variations along the Line of sight, LOS. Validation was represented by the comparison of the recent TSX displacement results with field GNSS data. The project leverage the investment in purchasing a large number of synthetic aperture radar single look complex (SAR SLC) data via *two successful DLR proposals (i.e., LAN1444 and LAND0421)* and *one ESA AO CAT-1 proposal (i.e., Project 12793)*, PI's M. Necsoiu and I. Armas. Access to a large number of datasets is important in monitoring long-term processes; in addition this is important because the quality of results depends on the number of acquisitions employed for the interferograms generation, an aspect that is very well researched and documented in well renowned literature in the field [8, 18].

In 2014, 24 high resolution images acquired from the TSX satellite (*http://sss.terrasar-x.dlr.de*) between 2011 and 2014 were processed by Dr. Eng. Marius Necsoiu from SwRI, USA. The images were selected from a larger pool of SAR images, after consulting weather databases which helped eliminating the images acquired under adverse weather conditions. SAR images were initially co-registered, then the coherence was extracted and finally geocoded. The processing of TSX data identified a high density of Persistent Scatterers, with approximately 600 000 points covering mainly the urban area of Bucharest. GNSS locations were cross checked on high-res optical images and 20 ground points (including 2 permanent stations) were selected. All these points were (1) characterized by high coherence on radar images; (2) were on the ground; (3) were situated in large vacant spaces (i.e., bare soil); (4) far away from radar obstacles such as trees.

After choosing their location (Fig. 8), the GNSS points were materialized and surveyed periodically. The materialization of the GNSS points was represented by marks specially built for the current project.

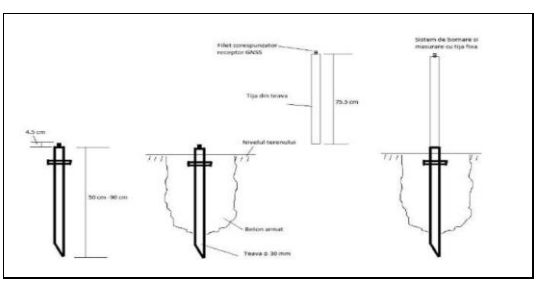

Fig. 7 Materialization system of the GNSS points

The marks consisted in tubes of 50-90 cm, burried in concrete. The marking system permitted a forced centering of the receptors on the mark, by using metal bars of fixed height (Fig. 7). This type of materialization eliminates the errors caused by receptor's height determination.

Five GNSS survey sessions were organized in 2014. The sessions were scheduled according to TerraSAR-X satellite's acquisition dates, in order to capture the same ground movements. The vertical and horizontal determinations resulted from the GNSS campaigns represented the initial field data necessary for validating the displacemetns of the SAR.

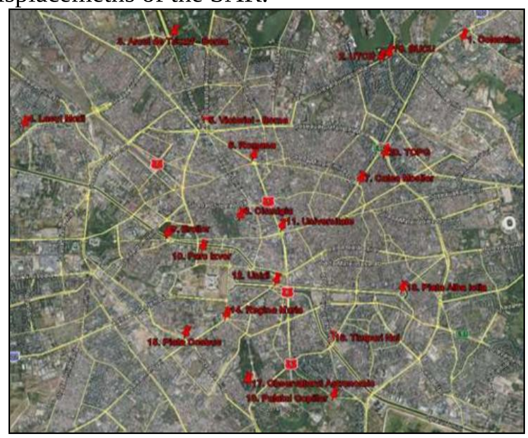

Fig. 8 GNSS positioning points of the monitoring geodetic network

The LOS components derived from GNSS data have been compared with those of the SAR scatterers closest to the GNSS markers (never coinciding). For each location, the vertical reading was projected in the line-of-sight (LOS) of the SAR sensor. These readings were compared with displacement values determined at PS locations within 100 m from the GPS nodes, by eliminating all scatterers on buildings. An alignment of the time scales has been necessary. The comparison has generally shown a good agreement.

The third task was to identifying linear/non-linear landscape evolution patterns. Instability is a common feature of earth surface processes and many authors have suggested that chaos is likely in landscape evolution **[**27, 28]. A dynamical system is nonlinear if the outputs (responses) are not proportional to the inputs (stimuli, or disturbances) across the entire domain. Nonlinear phenomena give rise to complex behavior that is not possible in linear systems. However, nonlinear systems may be simple and predictable, and complexity may have different roots than nonlinearity.

For this task, we chose to monitor the industrial parks, located toward the periphery of the city and representing large water consumers during the communist era, in comparison to their surroundings. The analysis of displacement trends over important industrial park was based on three sets of SAR satellite data collected over 20 years, highlighting the situation before and after 2000, when important water consuming industries were shut down. The necessary water was being extracted from the deep captive groundwater of the Frăteşti geological strata (especially bed A). Therefore, shutting down of a great number of factories in the last two decades might have had an important influence on the groundwater recharge. Only in 15 years, between 1990 and 2005, the water necessity for industrial purposes in Bucharest was halved. The identified patterns were of subsidence (or stability in areas of general uplift) for the period immediately following the communist era, characterized by intense exploitation of the ground water, and a returning to the zonal dynamic pattern after shutting down the main industrial factories and decreasing the water necessity on the industrial platforms. Results were presented at Fringe, ESA workshop in Italy [3]. The analysis of the dynamic patterns was done by mathematician Diana Mendes, from ISCTE-IUL Lisbon, results showing displacement time series with very persistent long memory behaviour (work in progress).

4. Conclusions

Characteristic for Bucharest is the weak useful signal in radar processing, the results needing validations through complex monitoring measurements on the ground.

The innovation of this project is the interconnected manner in which data is gathered from various scientific disciplines in order to integrate the ground displacement patterns into a dynamic and as accurate as possible representation of the area's geomorphological evolution, which is consistent with other environmental information.

In case of ground displacement interferometry products, the difficulty is that meaningful information is related to different spatial-temporal windows. These spatial-temporal windows have to be identified and understood through inter and multidisciplinary interpretation. The project is proposing a complex multi-scale approach of identifying ground displacement trends based on the integration of InSAR, geodesic, geologic, geomorphologic and hydrogeologic -based information into a unitary and explanatory environment.

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