Differential SAR Interferometry for the Monitoring of the UNESCO World Heritage Sites

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Abstract
Persistent Scatterer Interferometry and Small Baseline Subset Interferometry enable the detection, measurement and monitoring of ground displacements. These differential synthetic aperture radar interferometry techniques were applied to investigate the ground stability of the Historic Centre of Sighisoara, a cultural UNESCO World Heritage Site. In line with the objectives of the "Open Initiative on the Use of Space Technologies to Support the World Heritage Convention", the monitoring of Sighisoara World Heritage Site was performed based on Earth Observation data. A multi-temporal series of very high resolution TerraSAR-X data was analyzed and processed and the results provide the local authorities in-charge of the site protection and conservation a basis for informed corrective measures and strategies.

Keywords
Differential SAR interferometry, TerraSAR-X, Historic Centre of Sighisoara, World Heritage Site, Earth Observation

1. Introduction

Earth Observation (EO) has become a valuable tool for cultural and natural heritage monitoring considering that it allows the generation of complete, consistent, accurate and timely information, as a growing number of EO satellites are launched every year. Consequently, the data archives are continuously enlarging, thus providing a huge amount of data that can be used to monitor the World Heritage Sites.

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Based on long-term EO data it is possible to extract useful information that help not only to understand how a World Heritage Site is affected by changes and the role played by the human activities in these changes, but also to facilitate the formulation and implementation of appropriate protection and conservation policies and strategies.

One of the most important factors for sustainable strategies is represented by the information on ground and structural stability. The increased development and launch of very high resolution synthetic aperture radar (SAR) sensors opened the door to a wide range of innovative applications. On one hand, multi-temporal SAR satellite imagery offers a unique insight on the past subsidence trends and provides the current status on terrain deformation. On the other hand, very high SAR data enable the investigation of the buildings stability. New differential SAR interferometric (DInSAR) techniques that enable the ground deformation/displacement monitoring up to a few millimeters have been developed. These techniques are represented by Persistent Scatterers Interferometry (PS-InSAR) and Small Baseline Subset Interferometry (SB-InSAR) and they are currently the most appropriate solution for the monitoring of a World Heritage *cultural* or *natural* site that might be subject to ground displacement.The displacement information represents the foundation for sustainable heritage protection and conservation policies that include the potential required mitigation measures.

UNESCO, the United Nations Educational, Scientific and Cultural Organization, maintains the World Heritage List of properties considered of "outstanding value to humanity" [1]. At this moment (April 2015), the List includes 1007 World Heritage Sites. The Romanian properties inscribed on the World Heritage List consists of the Danube Delta, the Churches of Moldavia, the Monastery of Horezu, the Dacian Fortresses of the Orastie Mountains, the Wooden Churches of Maramures, the Villages with Fortified Churches in Transylvania, and the Historic Centre of Sighisoara [2].

In 2003, UNESCO and the European Space Agency (ESA) signed the "Open Initiative on the Use of Space Technologies to Support the World Heritage Convention" that has the goal to protect, monitor, document, present and share the World Heritage sites. In this context, the term "space technologies" refers mainly to EO and secondly to other technologies such as navigation, positioning, communication [3].

The potential of EO satellite imagery for the monitoring of cultural and natural World Heritage Sites was demonstrated by a significant number of scientific studies conducted for various test areas [4], [5], [6], [7], [8].

2. Historic Centre of Sighisoara and very high resolution satellite imagery

Located in the heart of Romania (N 46 13 04, E 24 47 32), in the Mures County, the Historic Centre of Sighisoara was inscribed on the World Heritage List in 1999 as a *cultural* site due to its architectural and urban monuments that were built by the German craftsmen and merchants starting with the 13th century. According to the UNESCO description [9], Sighisoara "is a fine example of a small, fortified medieval town which played an important strategic and commercial role on the fringes of central Europe for several centuries".

A considerable number of significant monuments and buildings are still present today in the Sighisoara Citadel, i.e. the Church on the Hill, the Joseph Haltrich High School, the City Hall, the Monastery Church, the Venetian House, the Scholars' Stairs, the Stag House, the St. Joseph Roman-Catholic Church, the Georgius Krauss House, and the towers that were used in the past to guard the fortified settlement. 14 towers were originally built by the guilds of craftsmen, out of which 9 are still standing, namely the Clock Tower (Figure 1), the Tanners' Tower, the Tailors' Tower, the Furriers' Tower, the Ropemakers' Tower, the Butchers' Tower, the Blacksmith Tower, the Shoemakers' Tower, and the Tinkers' Tower.

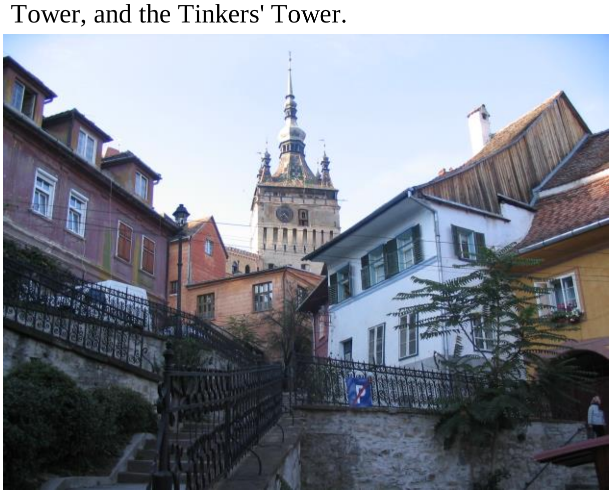

Fig. 1. The Clock Tower - Historic Centre of Sighisoara symbol

In the last years, the city of Sighisoara has been affected by floods that led to landslides that damaged some parts of the Historic Centre external wall, thus threatening the integrity of the World Heritage site. Such events, caused by heavy rainfalls, have been reported in the local press and there was a general concern that the Sighisoara Citadel might be in danger. Moreover, the UNESCO monitoring reports [10] corresponding to 2005-2012 mention the "deterioration of monuments in general and fortifications in particular" and the "lack of protection and maintenance measures, local responsibility and funding strategies".

In line with the objectives of the "Convention Concerning the Protection of the World Cultural and Natural Heritage" adopted by UNESCO in 1972, each State Party has the obligation to evaluate the state of conservation and identify the threats that might endanger the national World Heritage Sites [11] and the outcomes are periodically reported to the UNESCO World Heritage Committee.

At the moment, EO satellite imagery can be favorably used for the monitoring of the UNESCO World Heritage Sites. Both cultural and natural heritage can strongly benefit from the usage of satellite imagery, as their spatial, spectral and temporal resolutions are constantly improving with every new mission. In addition, the spatial resolution of the optical and SAR imagery (especially the data acquired by the X-band sensors) is presently adequate for the monitoring of cultural heritage sites, considering the required level of detail in comparison with the natural heritage sites. Apart from the remote sensing approaches that enable only the identification of landscape changes, the DInSAR techniques also provide information on ground (and structural) displacement.

For the monitoring of the Historic Centre of Sighisoara, a multi-temporal series of TerraSAR-X (TSX) High Resolution SpotLight (HS) images was programmed and acquired between March and October 2014. TerraSAR-X (Figure 2) is a side-looking X-band SAR equipped with an active antenna which is capable of acquiring data in different imaging modes. The platform's nominal orbit height at the equator is 514 km, orbit inclination 97.44^0 and the orbit repeat cycle is 11 days. TerraSAR-X was launched in 2007 and TanDEM-X in 2010. The TanDEM-X mission has the goal of acquiring data for a new global digital elevation model (DEM).

The HS images cover an area of approximately 5 km x 10 km (Figure 3) and have 2.1 m ground range resolution and 1.1 m azimuth resolution. Simple VV polarization and a bandwidth of 300 MHz define the HS data. The images were acquired from a descending orbit (orbit 47) with a view angle of 35^0 (beam spot 038R) at a revisiting time of 11 or 22 days. The list of TSX HS data is presented in Table 1. The last column of the table shows the perpendicular (normal) baselines computed in relation to the master image acquired on the 17th March 2014. The processing of the TSH HS data have been performed based on ENVI SARScape, the Interferogram Stacking module.

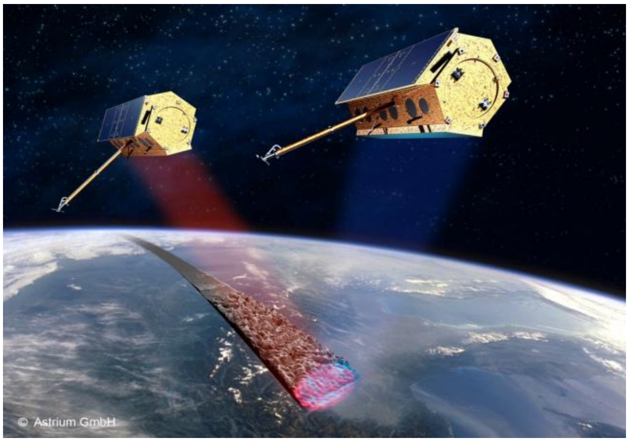

Fig. 2. Artist impression of TerraSAR-X and its twin satellite TanDEM-X on orbit (© Airbus Defence and Space)

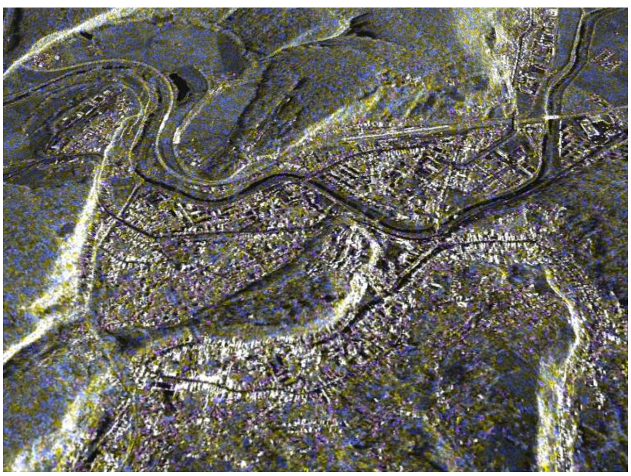

Fig. 3. TerraSAR-X preview image (medium resolution) covering the Historic Centre of Sighisoara (© DLR 2014)

Table 1. List of TerraSAR-X HS images used for the ground and structural monitoring of the Historic Centre of Sighisoara

TSX HS	Acquisition date	Normal baseline [24]
1.	06.03.2014	-37.036
2.	17.03.2014	0
3.	08.04.2014	-216.597
4.	19.04.2014	-70.204
5.	30.04.2014	160.622
6.	11.05.2014	23.996
7.	22.05.2014	52.552
8.	02.06.2014	-77.312
9.	13.06.2014	114.147
10.	24.06.2014	72.275
11.	16.07.2014	69.136
12.	27.07.2014	4.463
13.	18.08.2014	14.844
14.	29.08.2014	-100.386
15.	09.09.2014	-33.472
16.	20.09.2014	-117.869
17.	01.10.2014	-99.345
18.	12.10.2014	-50.991

3. Methodology and results

The monitoring of the Historic Centre of Sighisoara was performed based on multi-temporal Synthetic Aperture Radar (SAR) data, namely a series of 18 TerraSAR-X HS images. SAR is an active microwave imaging system. At present, there are numerous spaceborne SAR systems (i.e. TerraSAR-X, TanDEM-X, Radarsat, Sentinel-1, and Cosmo-SkyMed) that provide data for a wide range of applications [12], including thematic mapping, topographic mapping, deformation monitoring, and atmospheric delay mapping [13]. A complex SAR image is a two-dimensional matrix of pixels that store in the form of a complex number the amplitude and the phase of the signal backscattered by the ground targets towards the sensor [14], [15].

Geometrically similar to the conventional stereoscopic approach [12], SAR interferometry is based on the principle that the same area on the ground is viewed from slightly different positions [16]. This acquisition geometry can be obtained either simultaneously (single pass / cross-track interferometry) – with two radar systems on the same platform – or at different moments in time (repeat pass / along-track interferometry) - by repeated passes of the same satellite platform [12], [17], [18]. The phase difference between two radar images can be used to measure differences in the geometric path length or geometric distortions in the range direction [12], [19]. Two types of products can be derived based on SAR interferometry, namely DEMs and deformation/ displacement maps. In the first case the technique is called conventional (standard) interferometry (InSAR) and in the second case differential interferometry (DInSAR) [20], [21]. The input data for DInSAR consists of a pair of SAR images with a near-zero perpendicular (normal) baseline, a pair of SAR images with a non near-zero baseline (mandatory DEM), three SAR images, or two pairs of SAR images [20]. In all the cases, the SAR data should be selected according to certain criteria, out of which the value of the perpendicular baseline is the most important [20]. Recently, new DInSAR techniques based on multi-temporal (MT) SAR data have been developed [22]. According to [22], the space-borne DInSAR approaches include PS-InSAR, SB-InSAR, Differential SAR Tomography (D-TomoSAR), combined MT-InSAR, and SqueeSAR. All these techniques are suitable for cultural heritage monitoring [22]. In relation to the ground-based DInSAR approaches, Ground-Based SAR Interferometry (GB-InSAR) and Ground-Based Real Aperture Radar Interferometry (GB-InRAR) enable structural deformation monitoring based on static, respectively dynamic measurements [22].

PS-InSAR involves the identification of persistent scatterers

(PSs) within the generated interferograms. PSs represent radar reflectors that remain stable across time and with different acquisition geometries. PS-InSAR reduces the main errors specific to the conventional DInSAR processing, namely temporal and geometrical decorrelation, and atmospheric artefacts [23]. The following main steps are performed within the PS-InSAR workflow: computation of the complex and differential interferograms (based on a reference DEM), preliminary estimation of the candidate PSs, correction of the differential interferograms, and final estimation of the PSs in an iterative process [20], [23], [24], [25]. In the final step, a map showing ground and structural displacement over the selected time interval is generated by correlating the residual phase variation (as a function of time) to an expected temporal evolution model for each PS [15]. This steps involves phase unwrapping and DEM and baseline error correction [25].

SB-InSAR uses multilooked interferograms to monitor the evolution of ground displacement with a very high degree of temporal and spatial coverage [26]. In the first processing step, all the InSAR pairs with small baseline values are selected. Next, the corresponding interferograms are multi-looked in order to reduce the phase noise [20], [26], [27], [28]. In parallel, the coherence maps are generated. The most coherent pixels are extracted and their noise effects are considered negligible [12], [26], [29]. The processing chart continues with phase unwrapping using, in most of the cases, the minimum cost flow (MCF) algorithm [21], [26]. Afterward, the coherent pixels are analyzed over the unwrapped interferograms, considering that the topographic and atmospheric phase have been estimated and removed [26], [29].

The DInSAR techniques have limitations and benefits. The limitations are given mainly by the temporal decorrelation, the atmospheric artefacts, the availability of images, and the line-of-sight (LOS) measurement (higher performance in case of vertical displacements) [30]. [31]. Additionally, the magnitude of the deformation rates, the temporal and spatial sampling of the deformation phenomena, the geocoding precision, the linear deformation model assumption used by most of the processing software, and the problematic interpretation of the deformation results might limit the PS-InSAR relevance [31]. Nevertheless, PS-InSAR has the great advantage of accurately (1mm/year) detecting, measuring and monitoring ground displacements over large areas and structural displacements of individual features such as buildings, dams, other artificial structures [32], [31], regularly and at a relatively low cost [30]. Presently, the enormous archives of SAR imagery enable the investigation of past events for which other types of data are not available [30], [31]. In what SB-InSAR concerns, the main advantage of the technique is that it generates deformation maps with a high temporal sampling rate preserving at the same time the spatially dense displacement information [29].

The validation of the PS-InSAR results can be performed based on leveling data collected preferably at the same time with SAR data acquisitions [33]. Traditional leveling and GNSS data provide information with low spatial sampling density in comparison with satellite data processing [34]. Also, depending on the size of the investigated area, ground-truth campaigns are often difficult to put in practice. It is important to notice that the position of the PSs cannot be determined in advance of SAR data processing [31].

PS-InSAR have been successfully applied for the monitoring of Sydney [25], Barcelona and other Spanish cities [30], Amsterdam [31], Berlin [32], the German Ruhr area [33], Tianjin suburbs of China [34], [36], Las Vegas and Paris [35], the City of Dakar [37], Rome [38], Venice [39] and Tuscany region [40] and the examples could continue. Moreover, the great potential of TerraSAR-X for millimeter-scale structural deformation was proven by numerous scientific studies, as presented in [32], [33], [34], [35], [36], [39]. Thus, the significant advantages are given by the very high spatial resolution translated into a very large number of PSs with good long-term coherence, the less relevant atmospheric path delay errors and the relatively short 11-days revisiting intervals [33], [34], [35].

The PS-InSAR displacement map (Figure 4) corresponding to the Historic Centre of Sighisoara contains a very high density of PSs. Only in the area of the Citadel Hill the number of PSs is lower due to the presence of vegetation. There are approximately 15,000 PSs that have coherence higher than the threshold of 0.85. The elevation information was extracted from SRTM (© Jarvis A., H. I. Reuter, A. Nelson, E. Guevara, 2008, Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture, available at http://srtm.csi.cgiar.org). Using the mean displacement velocity of each PS, global statics have been computed. The results show that the mean value of the mean displacement velocity evens a value of -0.73 mm/year (standard deviation of ± 2.97 mm/year) with the investigated time interval (March – October 2014). The validation of the results was carried out based on SB-InSAR. The cross-validation showed a high agreement between the different DInSAR techniques.

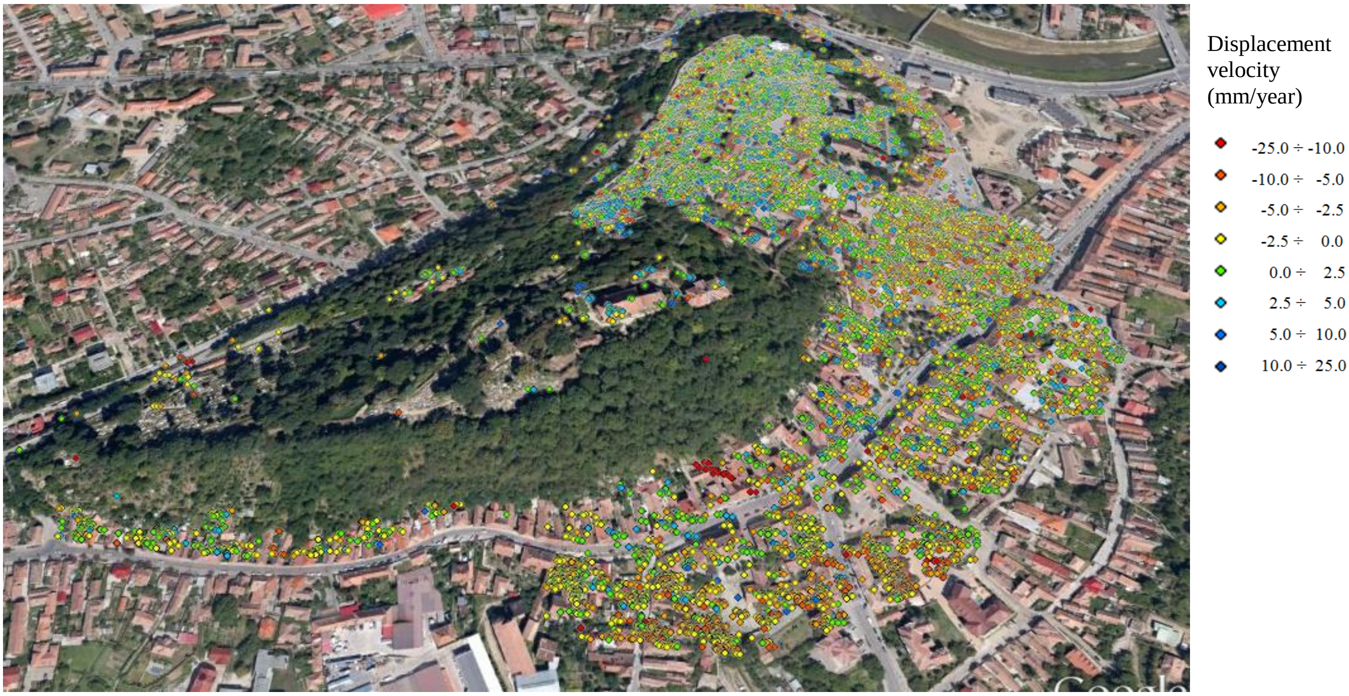

Fig. 4. PS-InSAR displacement map – Historic Centre of Sighisoara (background satellite imagery © 2015 Google)

4. Conclusions

The ground and structural stability of the Historic Centre of Sighisoara, a cultural World Heritage Site, was investigated based on a multi-temporal series of TerraSAR-X High Resolution SpotLight data that used processed using the PS-InSAR technique. The very large number of PSs enabled the monitoring of the ground and structural displacements in the March – October 2014 time framework. The average overall mean displacement velocity equalizes -0.73 mm/year with a standard deviation of ± 2.97 mm/year.

The PS-InSAR technique allows the estimation of the displacement velocity at millimeter level. Although the technique has yet some limitations, it has the definite benefit of providing accurate and useful displacement information both over very large areas and at the level of individual features, as extensively demonstrated by previous scientific studies. By providing detailed displacement information, the study may improve the measures that have to be adopted by the responsible authorities for the protection and preservation of the Historic Centre of Sighisoara. The millimeter-level displacement information provided by the space-borne DInSAR techniques represents a preventive diagnosis and should be validated based on ground-truth data (i.e. leveling, GNSS or GB-InSAR/GB-InRAR data).

As future work, the development of a pilot monitoring service for all the Romanian cultural and natural World Heritage Sites using the most appropriate Earth Observation technology has already started. The monitoring service will be designed to meet the different requirements of each site.

The monitoring of both *natural* and *cultural* sites using advanced space technologies will offer very accurate results that can help the local authorities to better understand the characteristics of each site in order to take the best protection and preservation measures.

Also, from the social and economic point of view, the monitoring service will have an useful function as it offers information regarding the local World Heritage Sites state of conservation and supports the implementation of corrective measures before irreversible damage might occur.

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