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# Earth Observation for the World Cultural and Natural Heritage

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**Abstract**

The main goal of UNESCO (United Nations Educational, Scientific and Cultural Organization) is to "encourage the identification, protection and preservation of cultural and natural heritage around the world considered to be of outstanding value to humanity" (World Heritage Convention). To date (April 2015), UNESCO World Heritage List consists of 1007 cultural (monuments, group of buildings, sites) and natural (natural features, geological and physiographical formations, natural sites) properties, 46 of them being considered under threat. The monitoring of the sites included on the UNESCO World Heritage List can be performed based on Earth Observation (EO) data. Nowadays, remote sensing is an excellent monitoring tool due to the recently launched satellite missions that enable the acquisition of very high resolution optical data (with an information content similar to aerial imagery) together with a wider offer of spectral bands. Not only the development of remote sensing sensors is impressive, but also the creation of new synthetic aperture radar interferometric (InSAR) techniques that enable the ground deformation/displacement monitoring up to a few millimeters, based on multi-temporal series of synthetic aperture radar (SAR) data. 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 Earth Observation and secondly to other technologies such as navigation, positioning, communication, etc. In accordance with the "Open Initiative", the study aimed at monitoring the Historic Centre of Sighisoara, a cultural heritage site inscribed on the World Heritage List in 1999 due to its architectural and urban monuments that were built starting with the 13th century. The results provide the Romanian National Commission for UNESCO and the assisting responsible authorities a support for informed decisions and may represent the foundation of a pilot monitoring service for the Romanian natural and cultural heritage sites inscribed on the UNESCO World Heritage List.


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## 1. Introduction

Established in 1945, UNESCO has a proactive role in "the conservation and protection of the world's inheritance of books, works of art and monuments of history and science" (Meskell et al., 2015). The concepts and guidelines in regard to the development of effective practices for the heritage conservation, planning and management are documented in the Convention Concerning the Protection of the World Cultural and Natural Heritage adopted by the General Conference of UNESCO in 1972 (Heras et al, 2013; Meskell et al., 2015).

The World Heritage List (http://whc.unesco.org/en/list/) encompasses exceptional and astonishing properties, spread all over the continents. From Stonehenge in the United Kingdom of Great Britain and Northern Ireland through the City of Bam in Iran, Taj Mahal in India, the Great Wall of China, Stone Town of Zanzibar in the United Republic in Tanzania, Iguazu National Park in Argentina and the Grand Canyon in the United States of America, the humankind has strived to preserve the cultural and natural heritage in pursuance of passing it on to the future generations.

UNESCO identified 14 primary factors/threats affecting the World Heritage properties, namely the urban sprawl, pollution, biological resource use/modification, physical resource extraction, local conditions affecting physical fabric, social/cultural uses of heritage, climate change and severe weather events, sudden ecological or geological events, management and institutional factors, transportation and utilities infrastructure, invasive/alien or hyper-abundant species, and other human activities and factors such as the deliberate destruction, terrorism or civil unrest (http://whc.unesco.org/en/factors/). In the context, the accurate monitoring of the state of conservation provides essential and timely information for the implementation of counteracting measures before irreversible damage might occur. Given the very large extent of some properties, especially in the case of the world natural heritage sites or the level of detail needed for the assessment of the cultural sites, satellite-based Earth Observation (EO) enables the responsible authorities to protect, monitor, document, present and share the World Heritage Sites. EO perfectly fulfils the purpose of the "Open Initiative on the Use of Space Technologies to Support the World Heritage Convention" that was signed by UNESCO and the European Space Agency (ESA) in 2003 (Ito, 2011).

The Romanian properties included on the World Heritage List are represented by the Danube Delta (Figure 1), the Churches of Moldavia (Figure 2), the Villages with Fortified Churches in Transylvania (Figure 3), the Monastery of Horezu (Figure 4), the Dacian Fortresses of the Orastie Mountains (Figure 5), the Wooden Churches of Maramures (Figure 6) and the Historic Centre of Sighisoara (http://www.cnr-unesco.roen/patrimoniu.php). The latter was inscribed on the World Heritage List in 1999 and it represents "an invaluable testimony to the culture of the Transylvanian Saxons and an outstanding example of a small fortified city in the border region between the central and the south-eastern Europe" (http://whc.unesco.org/en/list/902). A few years ago, the local press reported that the flood-triggered landslides damaged parts of the Historic Centre external wall, thus threatening the integrity of the cultural site. A number of images acquired by EO satellites were exploited in order to evaluate the conservation state of the Historic Centre of Sighisoara, a cultural heritage site.

Figure 1. Danube Delta
(© 2003 CNR UNESCO)

Figure 2. Churches of Moldavia
(© 2003 CNR UNESCO)

Figure 3. Fortified Churches Transylvania
(© CNR UNESCO)

Figure 4. Monastery of Horezu
(© 2003 CNR UNESCO)

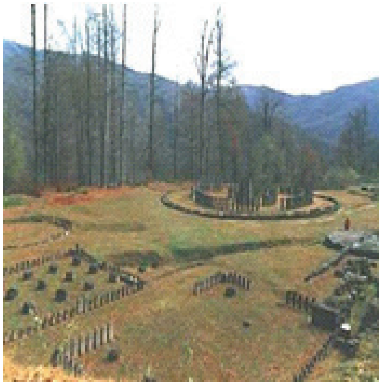

Figure 5. Dacian Fortresses - Orastie Mountains
(© 2003 CNR UNESCO)

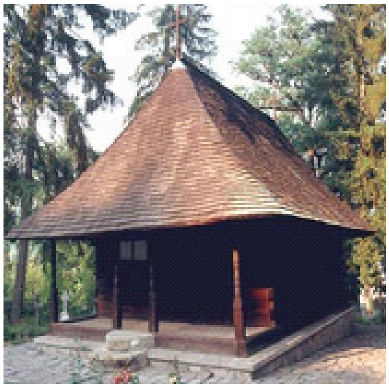

Figure 6. The Wooden Churches Maramures
(© 2003 CNR UNESCO)

## 2. Earth Observation satellite data collection and processing

### *2.1. Spatial data infrastructure*

UNESCO has recently started the development and implementation of an integrated World Heritage database that will also incorporate satellite images and the results generated from the analysis and processing of such images. This comprehensive database will represent a significant component of a unique State of Conservation Information System (SOC) that will enable an improved understanding and preservation of the World Heritage (http://whc.unesco.org/en/soc/).

In line with the current trend, a spatial data infrastructure was defined for the Historic Centre of Sighisoara (Figure 7 and Figure 8) by creating a thorough, accurate and updated Geographic Information System (GIS) geo-database. It embodies vector and elevation data, aerial and satellite images, and satellite-derived information. The vector data layers consists of the administrative boundaries, neighboring places, rivers, roads and railways network, and land use/land cover data (i.e. the Land Cover Classification System and Corine Land Cover datasets).The satellite imagery is manifold in terms of the imaging sensor and the spatial and spectral resolution. The images acquired by SPOT 5 (Figure 9), TanDEM-X (Figure 10), Landsat 8 (Figure 11), Pléiades (Figure 12), enable a comprehensive view of the monitored World Heritage Site as the information provided by the optical and synthetic aperture radar (SAR) sensors complement each other. The elevation information was extracted from two digital elevation models (DEMs), namely SRTM (© Jarvis A., H. I. Reuter, A. Nelson, E. Guevara, 2008,SRTM data V4, International Centre for Tropical Agriculture, available at http://srtm.csi.cgiar.org) and SPOT 3D (Figure 13 and Figure 14). The Landsat imagery is courtesy of NASA Goddard Space Flight Center and U.S. Geological Survey.

Figure 7. Sighisoara
(© 2003 CNR UNESCO)

Figure 8. Historic Centre of
Sighisoara (© 2015 Google Earth)

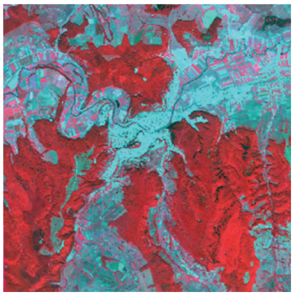

Figure 9. SPOT 5 image
(© 2007 CNES)

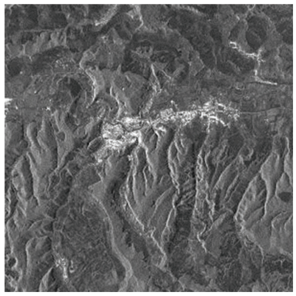

Figure 10. TanDEM-X image
(© 2011 DLR)

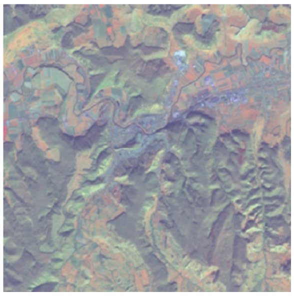

Figure 11. Landsat 8 image (© 2013 NASA/USGS)

Figure 12. Pléiades image (© 2013 AIRBUS Defence & Space)

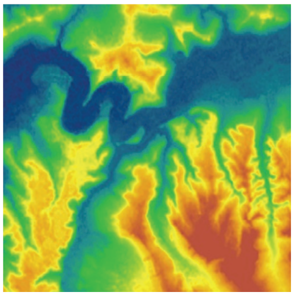

Figure 13. SPOT 3D DEM - 2D visualization (© 2010 CNES)

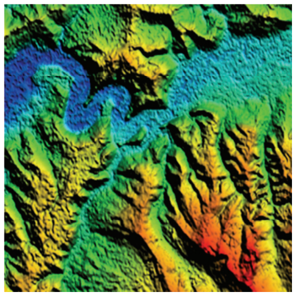

Figure 14. SPOT 3D DEM - 3D visualization (© 2010 CNES)

A multi-temporal series of 18 TerraSAR-X (TSX) High Resolution SpotLight (HS) images was programmed and acquired between March and October, 2014. The HS images cover an area of approximately 5 km x 10 km centered on the Historic Centre of Sighisoara and have 1 m spatial resolution and simple VV polarization. The images were acquired from a descending orbit with a view angle of 350 at a revisiting time of 11 or 22 days.

*2.2. Remote sensing processing methods*

Generally, the monitoring of a World Heritage Site can be performed using several remote sensing techniques. A classical approach is change detection based on at least two optical satellite images acquired at a certain time interval over the same area of interest. In this case, the analysis of the land cover (LC) and land cover change (LCC) in time and space is a convenient technique, especially in the case of the natural sites. Depending on the spatial and spectral resolution, it can detect coarse and fine scale status and change that might be validated using ground truth data (Wondie et al., 2011). For a thorough analysis, a multi-temporal series of images acquired by optical spaceborne sensors can be used. This technique enables the monitoring of the conservation state over a specific time frame and identifies the major changes in the site itself and its surroundings (Giri et al., 2007). But even in this case, the results show only changes in the landscape and not proofs of ground deformation that might endanger the World Heritage Site.For a highly detailed and accurate assessment of ground displacement, subsidence, landslides or building stability, the new differential SAR interferometry (DInSAR) techniques are currently the most appropriate solution for cultural heritage monitoring (Zhou et al., 2015). These techniques require large series of multi-temporal SAR data. An example of a DInSAR method applicable to urban areas is represented by Persistent Scatterers Interferometry (PS-InSAR). This technique is very sensitive to small displacements (millimeter-level motions) and it has the great advantage of monitoring wide areas while offering the possibility to measure independent features such as buildings (Zhou et al., 2015). Another example of a DInSAR technique is Small Baseline Subset Interferometry (SB-InSAR) that also monitors the evolution of ground displacement with a high degree of temporal and spatial coverage. This technique is mainly recommended for the monitoring of the cultural heritage sites located in non-urban area (Zhou et al., 2015). In some cases, the monitoring of the World Heritage Sites additionally requires information related to the elevation. Optical stereoscopy based on aerial or satellite imagery offers acceptable results when if certain criteria are met at the same time, namely an optimal base-to-height ratio, a minimum time interval between the acquisition of the two images and the maximum percent of overlap between the two images (Durand, 2000). Another approach is conventional radar interferometry (InSAR) that consists in the use of the phase of a radar signal by comparing two SAR images acquired simultaneously or in a certain time interval (Massonnet and Souyris, 2008). Likewise, the results are influenced by the quality of some parameters such as the angle and direction of acquisition, the geometric and the temporal baseline, the moment of acquisition, the coherence and the atmospheric conditions (Ferretti et al., 2007).

The interpretation of remote sensing satellite-derived information might lead to erroneous results if validation based on ground truth data is not performed. DInSAR techniques, and in particular PS-InSAR, require the execution of terrestrial survey actions and the integration of ancillary and background data (Tapete and Cigna, 2011).

The potential of the remote sensing techniques was demonstrated in a large number of studies focused on different World Heritage Sites around the world. Examples include the Simen Mountains National Park in Ethiopia (Wondie et al., 2011), the Historic Centre of Rome, Italy (Cigna et al., 2014), Southern and Northern Tuscany, Italy (Tapete and Cigna, 2011), the Ming Great Wall of China (Chen et al., 2010), the cultural heritage in Cyprus (Hadjimitsis et al., 2013), the Sundarbans in Bangladesh (Giri et al., 2007), and the Lines and Geoglyphs of Nasca in Peru (Tapete et al., 2014). Further, within the "Open Initiative" several projects were developed for the monitoring of the World Heritage Sites located in Rwanda, Uganda, Democratic Republic of Congo, Irak, Russia, Brazil, Argentina, Guatemala, Peru, South Africa and Mexico (http://www.unesco.org/science/remotesensing/?lang=en).

In the present study, PS-InSAR was applied to investigate whether the architectural and urban monuments located in the Historic Centre of Sighisoara are affected by displacements. The processing of the TSX HS series of images was performed with the Interferogram Stacking module of the ENVI SARscape software. The method uses a single-master image mode.

## 3. Results and discussion

The displacement map generated using the PS-InSAR technique contains 14,673 persistent scatterers (PSs) within the Historic Centre of Sighisoara. A threshold of 0.85 was set for the PSs coherence in order to select and process the master-slave InSAR pairs with a high quality interferometric phase. The mean displacement velocity was computed for each PS. The overall statistics show that the mean value of the mean displacement velocity equalizes -0.73 mm/year (standard deviation of ± 2.97 mm/year). Based on the PSs density and the temporal and spatial baselines, the precision estimate corresponds to ± 2.78 mm/year. Three relevant examples were extracted from the PS-InSAR displacement map for a detailed analysis, namely the Church of St. Nicholas (Figure 15a, b), the Clock Tower (Figure 16 a, b) and the Tailors' Tower (Figure 17 a, b).



Figure 15. Church of St. Nicholas. According to UNESCO, it represents an "edifice typical of the Gothic architecture of Transylvania. Perched on the hill, it can be reached by a ramp staircase of 175 steps. It has been protected by a wooden roof since 1642. The decorative sculpture on the facade reflects Central European influences" (http://whc.unesco.org/en/list/902). The displacement velocity ranges from -0.49 mm/year to +4.52 mm/year. The mean velocity is +2.58 mm/year. The upper image (a) illustrates the persistent scatterers overlapped on a satellite image acquired in 2012 (© 2015 Google). The left image (b) is also extracted from Google Earth (© 2015 Google).


Displacementvelocity (mm/year)

- -25.0 ÷ -10.0
- -10.0 ÷ -5.0
- -5.0 ÷ -2.5
- -2.5 ÷ 0.0
- 0.0 ÷ 2.5
- 2.5 ÷ 5.0
- 5.0 ÷ 10.0
- 10.0 ÷ 25.0

b

Figure 16. Clock Tower. The official UNESCO description points out that it "plays a special role as the symbol of the town, for it was placed under the responsibility of the city council, which held its assemblies there until 1556. Situated in the middle of the southern fortification wall, it dominates the three squares of the historic centre and protects the stairway connecting the upper town and the lower town. It now houses a museum" (http://whc.unesco.org/en/list/ 902).On the LOS, the minimum displacement velocity is -2.27 mm/year, while the maximum value equals +5.20 mm/year. The mean displacement velocity is +1.29 mm/year. (a)Results generated from the processing of the TerraSAR-X images and overlapped on satellite imagery (© 2015 Google).(b) Imagefrom the personal archive.


Displacement velocity (mm/year)

- -25.0 ÷ -10.0
- -10.0 ÷ -5.0
- -5.0 ÷ -2.5
- -2.5 ÷ 0.0
- 0.0 ÷ 2.5
- 2.5 ÷ 5.0
- 5.0 ÷ 10.0
- 10.0 ÷ 25.0

b

Figure 17. Tailors' Tower. It is one of the "nine towers of the original 14 still stand and can be distinguished by their shapes" (http://whc.unesco.org/en/list/902). The displacement velocity is between -3.76 mm/year and +4.33 mm/year, with a mean value of + 0.01 mm/year. The Tailors' Tower is illustrated (a) in the satellite image (© 2015 Google) and (b) in the ground level photograph (© 2015 Google).

One major aspect that should be considered when interpreting a PS-InSAR displacement map is that the velocity is measured in the slant range direction, i.e. the Line of Sight (LOS). Thus, if the slant range distance between the sensor and the target decreased, the PSs are represented in the blue color and signify positive displacements. Similarly, an increased distance denotes a negative sign displacement symbolized by the red color. Moreover, the PS-InSAR displacement information corresponds only to the descending acquisition geometry.An exhaustive assessment of the deformation pattern requires the integration of the ascending acquisitions as well. Ideally, the EO-derived monitoring results should be validated based on ground-truth data. In the case of the DInSAR techniques, the most convenient solution is the Ground-Based SAR Interferometry (GB-InSAR), as proposed by (Zhou et al., 2015). However, ground-truth campaigns are often difficult to put in place due to the extent of the area and the operational costs. Therefore, the validation of the results should be performed using another monitoring method.

The promising results obtained for the Historic Centre of Sighisoara support the concept of an Earth Observation based monitoring service for all the Romanian properties inscribed on the World Heritage List. The proposed service will be tailored to meet the specific characteristics of each site and it will take into account the current negative factors. An overview of the proposed methods and EO data is presented in Table 1. The information related to the factors affecting the properties was extracted from the periodic reports submitted to UNESCO by the authorities in charge with the site management. The reports were elaborated in 2014.

Table 1. EO data and processing methods for a monitoring service designed for the Romanian World Heritage Sites

| World Heritage Site | Type | Current negative factors | EO monitoring method(s) | EO data |
|---|---|---|---|---|
| Danube Delta | natural | Illegal activities<br>Erosion & siltation/ deposition | change detection | high resolution multi-temporal optical data |
| Churches of Moldavia | cultural | Water (rain/water table) | SB-InSAR<br>PS-InSAR | high resolution multi-temporal SAR data |
| Villages with Fortified Churches in Transylvania | cultural | Ground transport infrastructure | SB-InSAR<br>PS-InSAR | high resolution multi-temporal SAR data |
| Monastery of Horezu | cultural | Water (rain/water table) | SB-InSAR<br>PS-InSAR | high resolution multi-temporal SAR data |
| Dacian Fortresses of the Orastie Mountains | cultural | - | change detection | very high resolution optical data |
| Wooden Churches of Maramures | cultural | Micro-organisms | SB-InSAR<br>PS-InSAR | high resolution multi-temporal SAR data |
| Historic Centre of Sighisoara | cultural | - | PS-InSAR<br>SB-InSAR | high resolution multi-temporal SAR data |

## 4. Conclusions

The monitoring of the world cultural and natural heritage using Earth Observation offers definite benefits, namely the coverage of very large areas, the systematic investigation, and the multi-scale deformation detection.

Based on the PS-InSAR technique, the stability of the Historic Centre of Sighisoara could be determined at millimeter level. The TerraSAR-X images acquired in spotlight mode offer very high resolution and short revisiting times that enable the generation of a large number of PSs. The processing of multi-temporal X-band SAR data allowed the accurate measurement of the displacement velocity for individual buildings. The exceptional potential of TerraSAR-X data for monitoring studies was demonstrated anew, in addition to the previous research.

Of utmost importance is the validation of the results. Although problematic to put in practice, especially in the case of extensive areas, the collection of ground-truth continuous data in real time is recommended. Nevertheless, the disadvantage of ground monitoring is given by the fact that, in most of the cases, it targets individual structures, while the surrounding landscape is overlooked. As future work, the application of SB-SAR based on the same TSX HS dataset is foreseen for the cross-validation of the results considering the utterly different processing workflows and error sources.

The results of the study focused on the Historic Centre of Sighisoara support the UNESCO "Convention Concerning the Protection of the World Cultural and Natural Heritage" as each State Party must periodically provide reports regarding the state of conservation and any threats that one heritage site might be facing. With the support of the Romanian Commission for UNESCO, the study may improve the information flow and communication among site managers and conservation authorities and assist the responsible authorities to take protection and preservation measures based on accurate information. Furthermore, the study may represent the foundation of a pilot service for the monitoring of the Romanian natural and cultural sites inscribed on the World Heritage List. By using the most appropriate and affordable space technology, tailored to meet the distinct requirements of each site, the monitoring of both natural and cultural sites will offer very accurate results that may help the local authorities to better and thoroughly understand the characteristics of each site in order to take the best protection and preservation measures.

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