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Monitoring ground deformation of cultural heritage sites using SAR and geodetic techniques: the case study of Choirokoitia, Cyprus

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ABSTRACT

Currently, assessing geo-hazards, in cultural heritage sites takes place after the hazard has occurred. Monitoring the deformation of structures as a result of geo-hazards, including their surrounding areas facilitates the early recognition of potential risks and encourages effective conservation planning. This paper presents the integrated methods using SAR data, GPS/GNSS observations, and aerial images from UAVs to monitor ground deformation within the Choirokoitia UNESCO World Heritage Site in Cyprus. The Neolithic settlement of Choirokoitia is one of the most important prehistoric sites in the eastern Mediterranean. The field measurements collected at the Choirokoitia site were compared with SAR data to verify displacements in the area and to monitor potential geohazards over time. The Choirokoitia site is located on a steep hill, which makes it vulnerable to rock falls and landslides. The results indicated displacement rates at the order of 3cm per year and verified that long-term low-impact monitoring systems such as SAR images, UAVs and geodetic techniques can be used to monitor and assess potential geohazards on archaeological sites.

I. INTRODUCTION

Cultural heritage is highly vulnerable to geological disasters induced by earthquakes, volcanoes, floods and catastrophic landslides, as well as other non-catastrophic slow-onset geo-hazards that can slowly affect the integrity and accessibility of the heritage, such as slow-moving landslides, sinkholes, ground settlement and active tectonics. Even if these phenomena can be responsible for large damages, they are largely neglected in the literature (Gutiérrez and Cooper, 2002; Rohn *et al*, 2005; Canuti *et al*, 2009). The long-term vulnerability of cultural heritage is commonly focused on the heritage itself (i.e., degradation and corrosion of building materials) in response to environmental risks (Brimblecombe, 2000; Fort *et al*, 2006), without fully considering or understanding the entire geological and geotechnical context. Currently, assessing geo-hazards in cultural heritage sites takes place after the geo-hazard has occurred. However, the high costs of maintenance of cultural heritage sites directly enforce the prioritisation of the monitoring and conservation policies to ensure sustainable conservation. Monitoring the deformation of structures as well as their surroundings facilitates the early recognition of potential risks and enables effective conservation planning (Tang *et al* 2016).

On-site observation has been the most common way of monitoring cultural heritage sites and monuments in Europe. However, this procedure, that includes field surveying, ground-based data collection and periodical observations, can be time-consuming and expensive, especially over large or remote areas. (Themistocleous *et al*, 2016a). Deformation monitoring in cultural heritage sites is usually carried out by installing electrical sensors in selected structures with automatic systems for data acquisition and recording, or by using portable instruments with manual reading of data taken at fixed time intervals (Zhou *et al*, 2015; Garziera *et al*, 2007; Glisic and Inaudi, 2008). However, such methods can only acquire data of the monitored structure within the cultural heritage sites, not the entire area of the site and its surrounding landscape (Zhou *et al*, 2015). Moreover, the installation of monitoring devices, such as optical targets, permanent GNSS stations or inclinometers, on the heritage sites and monuments can lead to aesthetic and functional impacts that can affect the integrity and availability of the heritage.

The PROTHEGO project (www.prothego.eu) sought to develop and validate an innovative multi-scale methodology for the detection and monitoring of European Cultural Heritages exposed to natural hazards, namely monuments and sites potentially unstable due to landslides, sinkholes, ground settlement, active tectonics as well as monument deformation, all of which could be affected by climate change and human interaction. PROTHEGO sought to develop a new, low-cost methodological approach for the safe management of cultural heritage monuments and sites located in Europe, by integrating novel space technology based on radar interferometry (InSAR), long-term low-impact monitoring systems and indirect analysis of environmental contexts to retrieve information on ground stability and motion in the 400+ UNESCO's World Heritage List monuments and sites of Europe (Margottini *et al*, 2016; Themistocleous *et al*, 2016a).

II. STUDY AREA

The study area for the field monitoring was the UNESCO World Heritage Site of Choirokoitia in Cyprus, which is one of the four demonstration sites of the PROTHEGO project. The Neolithic settlement of Choirokoitia, occupied from the 7th to the 4th millennium B.C., is one of the most important prehistoric sites in the eastern Mediterranean (UNESCO). Included in the UNESCO World Cultural Heritage list since 1988, Choirokoitia is one of the best preserved settlements of this period in Cyprus and the Eastern Mediterranean. Located in the District of Larnaka, about 6 km from the southern coast of Cyprus, the Neolithic settlement of Choirokoitia lies on the slopes of a hill partly enclosed in a loop of the Maroni River. Occupied from the 7th to the 5th millennium B.C., the village covers an area of approximately 3 ha at its maximum extent and is one of the most important prehistoric sites in the eastern Mediterranean. It represents the Aceramic Neolithic of Cyprus at its peak, that is the success of the first human occupation of the island by farmers coming from the Near East mainland around the beginning of 9th millennium.

Figure 1. Choirokoitia, Cyprus.

Since only part of the site has been excavated, it forms an exceptional archaeological reserve for future study. To date, 20 houses have been excavated which were constructed with limestone, clay and brick. The site depicts how people lived in the Neolithic era which was mostly through agriculture and raising domestic animals. According to UNESCO, the site was officially abandoned in the 4th millennium BC. The reason for this still remains unknown (UNESCO).

III. MONITORNG GEO-HAZARDS

According to Margottini *et al*, (2015), the combined adoption of different survey techniques, such as 3D laser scanning and ground-based radar interferometry may be the best solution in the interdisciplinary field of cultural heritage preservation policies. Satellite radar interferometry is capable of monitoring surface deformation with high accuracy using precise ground measurements. Once vulnerable sites are identified by InSAR satellite imagery, local-scale monitoring and advanced modeling can be used to monitor the cultural heritage sites over time. The local scale monitoring methodology includes in-situ observation and remote sensing techniques, such as PS techniques, that are used to validate the impact of natural hazards. Topographic surveying using differential GNSS, images from Unmanned Aerial Vehicles (UAVs), photogrammetry and InSAR data are used to map slow ground movements, which are then compared and validated with ground based geotechnical monitoring in order to evaluate cultural heritage sites deformation trend and to understand its behaviour over time. As a result, areas exposed to potential risks and their evolution in time can be identified and crucial information can be provided to decision makers in order to protect cultural and heritage sites from natural hazards.

Local scale monitoring provides the opportunity to detect and analyze deformation phenomena for monitoring and predicting geo-hazards using field survey techniques to measure and document the extent of damage of the natural hazard on the cultural heritage site. The geodetic techniques can be used in combination with UAVs for documentation purposes and 3D modeling comparison. The aerial imagery obtained from the UAVs can be imported into Structure in Motion software to create rapidly and automatically generate a point cloud model and a 3D mesh model in order to document and monitor the extent of geo-hazards at the cultural heritage site. The ground based geotechnical monitoring can then be compared and validated with InSAR data to evaluate cultural heritage sites deformation trends.

Local scale monitoring can be used to assess the severity of these geo-hazards by using integrated field monitoring techniques. Research indicates that the integration of InSAR data and conventional surveying offers the best solution for monitoring geo-hazards in cultural heritage sites (Margottini *et al*, 2015; Novellino *et al*, 2018; Margottini *et al*, 2018). Geotechnical techniques are used to measure deformation over a relatively short measurement base. In-situ measurements using UAVs, total station, laser scanning and GPS/GNSS are then used to monitor the geo-hazards. (Themistocleous 2017; Themistocleous *et al* 2017a; Themistocleous *et al* 2017b).

A methodology was developed for local-scale monitoring in order to assess the risk from natural hazards on the archaeological sites and monuments from a geospatial perspective. The research methodology focused on long-term low-impact monitoring systems as well as indirect analysis of environmental contexts to investigate changes and decay of structure, material and landscape (Themistocleous *et al*, 2016a; Themistocleous, 2018). In addition, a multi-criteria analysis of the UNESCO sites in Cyprus to estimate the severity of each geo-hazard (Silvestrou and Themistocleous, 2018).

The methodology for the local scale monitoring begins with using InSAR images to identify natural hazards in the UNESCO World Heritage demonstration sites. When the InSAR ground motion data indicated that a natural hazard took place at or near the demonstration site, field monitoring and verification is used to document and measure the extent of the change caused by the natural hazard, if any. Documentation of the damage can be performed using laser scanning, photogrammetry, UAVs and/or drones. Measurements for calibration of these products are taken using GNSS and total station. After the change is identified using field verification, InSAR images are again used to verify and assess the extent of the damage to the cultural heritage site (Themistocleous *et al*, 2018). The methodology is presented in figure 2.

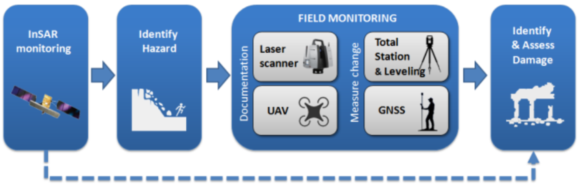

Figure 2. Methodology

A. *SAR Images*

By examining regions of interest from 800 km above the Earth's surface, Synthetic Aperture Radar (SAR) imaging satellites, Interferometric SAR (InSAR) and Persistent Scatterer Interferometry (PSI) processing techniques (Rosen *et al*, 2000; Ferretti *et al*, 2011; Crosetto *et al*, 2010) are capable of estimating, with up to millimetre precision, subtle and non-catastrophic, long-term and seasonal land processes. Such processes are triggered by a variety of natural and anthropogenic causes and drivers that can cause damage to the tangible heritage. Once vulnerable sites are identified by InSAR, detailed geological interpretation, hazard analysis, local-scale monitoring, advanced modeling and field surveying for the most critical sites will be carried out to discover possible cause and extent of the observed motions.

SAR images, acquired by active radar sensors, are processed with multi-interferogram methods, such as the Persistent Scatterers (PS), and are used to extract information on ground displacement that occurred across the areas of interest during the monitoring period, thereby providing an effective solution to measure large-scale surface deformations from space (Zhou *et al*, 2015; Ferretti *et al*, 2011; Hooper *et al*, 2012; Chen *et al*, 2013; Chen *et al*, 2012; Cigna *et al*, 2012; Cigna *et al*, 2014). In the Choirokoitia case study, 26 Cosmos Skymed SAR images from the years 2011-2017 were used in order to perform the PSI analysis.

B. *Imagery from Unmanned Aerial Vehicles (UAVs)*

UAVs have become a common tool in cultural heritage and archaeological research as they provide higher resolution images compared with satellite imagery. Remote sensing technologies on UAV platforms are extremely useful for the detection and monitoring of cultural heritage features (Themistocleous *et al*, 2014a; Themistocleous *et al*, 2014b; Themistocleous *et al*, 2014c; Agapiou *et al*, 2013). UAVs can be an efficient, non-evasive and low cost resource to document cultural heritage sites (Themistocleous *et al*, 2014a; Themistocleous *et al*, 2014b; Themistocleous *et al*, 2014c; Agapiou *et al*, 2013) and can be equipped with sensors that enable the production of an unprecedented volume of high-resolution, geo-tagged image-sets of cultural heritage sites (Themistocleous *et al*, 2014a; Themistocleous *et al*, 2014b; Kostrzewa *et al*, 2003; Ruffino and Moccia, 2015; Scholtz *et al*, 2011).

UAVs provide an affordable, reliable and straightforward method of capturing cultural heritage sites, thereby providing a more efficient and sustainable approach to documentation of cultural heritage sites (Themistocleous *et al*, 2015a; Themistocleous *et al*, 2015b; Themistocleous *et al*, 2015c; Lo Brutto *et al*, 2014; Burkhart *et al*, 2014; Colomina and Molina, 2014). Recent developments in photogrammetry technology provide a simple and cost-effective method of generating relatively accurate 3D models from 2D images (Ioannides *et al*, 2013; Themistocleous *et al*, 2015a; Themistocleous *et al*, 2015b; Themistocleous *et al*, 2014a; Themistocleous *et al*, 2015c). To document cultural heritage site under threat from geo-hazards, UAV images can be used to create orthophotos, dense clouds, 3D model and Digital Elevation Models (Themistocleous, 2017). It is recommended that the UAVs should be equipped with a 20MP camera to acquire images over the site with fixed ground control points for geo-referencing in order to produce a photogrammetric ortho-image and point cloud 3D model of the demonstration site and also for comparison over temporal intervals.

C. *Geodetic Network*

A geodetic network consists of a reference point and additional nodes, established at specific points of interest (i.e. points on peaks or ridges that may indicate/warn of a potential hazard) (Themistocleous *et al*, 2017a; Themistocleous *et al*, 2017c). Network points were measured regularly using satellite (GNSS) and ground measurements (via high precision total stations and levels) to estimate the potential relative motion with respect to the network reference point, during the life-span of the monitoring activity (figure 3). The number of points is a function of site vulnerability parameters as indicated by geology specialists. The network nodes (or control points) need to be incorporated into the site and placed in such way as to ensure mutual visibility with the total station setup at the reference point (Themistocleous *et al*, 2017a; Themistocleous *et al*, 2017b). There are various GNSS units that can be used to measure the geodetic network. Two types of receivers were used for data acquisition; (a) 3 Trimble R9s equiped with Zephyr 2 Geodetic GNSS antennas, and a Leica GS15 Smart GNSS receiver. The geodetic network consisted of a total number of four (4) points. The main control point was established on solid ground outside the area of interest, whilst the remaining three were set up in critical and carefully selected locations (i.e. on top of rocks or ridge lines) after consulting geologists and archaeologists to address high-risk areas within the site. (Themistocleous *et al*, 2017a; Themistocleous *et al*, 2017b).

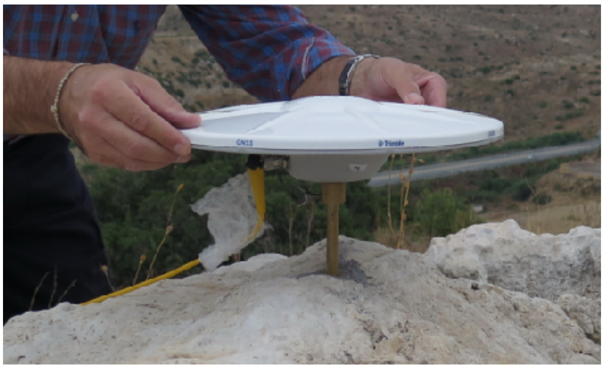

Figure 3. Geodetic network setup

IV. Results

In order to support field monitoring, geometric documentation of the area was performed using UAV systems and photogrammetry. This data was supported and geo-referenced using a geodetic network measured via contemporary GPS/GNSS receivers (modular Trimble® R9s and Trimble® Zephyr® 3 antennas) mounted on specifically designed metallic poles fitted in solid rock. The focus of the documentation is the reconstruction of the cross-sections over the identified areas of the demonstration site in order to investigate possible changes in the vertical and horizontal profiles of the remains. Under the framework of the PROTHEGO project, hundreds of images of the Choirokoitia site were taken using a UAV with an attached high-resolution camera. As part of the Local-scale monitoring of the Choirokoitia demonstration site in the PROTHEGO project, a UAV with an attached 20MP camera was used to acquire images over the site with fixed ground control points for geo-referencing in order to produce a photogrammetric ortho-image of the demonstration site and also for comparison over temporal intervals. The images were processed using photogrammetry, where the digital images acquired from the UAV are interpolated in order to create high resolution, scaled and georeferenced 3-D models from them. Digital Elevation Models (DEMs) were generated to examine any possible changes in the case study area over time (figure 4). The DEMS generated based on the images from February, 2017, November, 2017 and March, 2018 found there is a slight shift at the top peak of the hill.

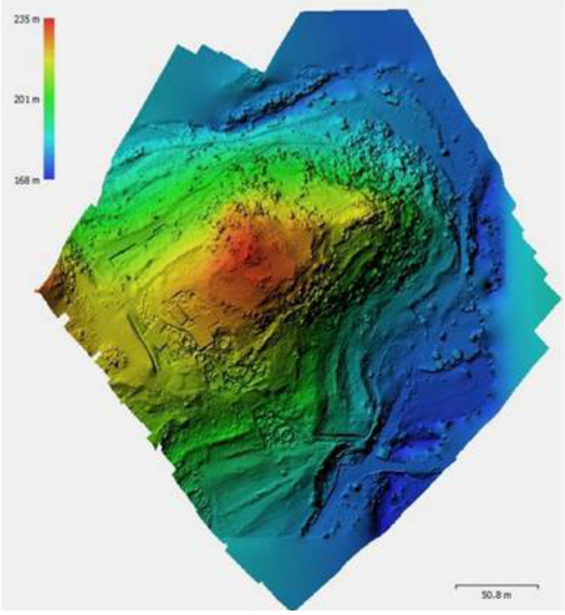

Figure 4. DEM generated from the UAV images using photogrammetry

Furthermore, two GPS/GNSS campaigns of the established network were carried out in the area of study within a 5-month period (19.05.2017 and 26.10.2017). In both cases, observations of 1Hz were collected for a timespan of six hours. The results of the GNSS control network processing during the study time frame are featured in Table 1. The four GNSS network points were measured to compute displacement in the East (DE), North (DN) and Up (DU) directions. The displacements were derived from topocentric coordinates with respect to the main network control point (CHR3).

Table 1. Results of GNSS Control network

GPS Station	Coordinates (LTM) Lat/Long	DE Meters	DN Meters	DU Meters
CHR1	231524.820 / 352001.675	+0.0023	-0.0025	-0.0027
CHR2	231314.725 / 351974.690	+0.0022	-0.0001	+0.0017
CHR3	231344.434 / 351922.148	+0.0000	+0.0000	+0.0000
PILR	231453.791 / 351980.692	+0.0024	+0.0001	**-0.0203**

The results of the GPS/GNSS campaigns indicate a change of 2cm in the Up component within the 5-month period. Furthermore, a PSI (Persistent Scatterer Interferometry) analysis was conducted on the Choirokoitia broader area to determine potential displacements (see Figure 5) using 26 Cosmos Skymed SAR images from the years 2011-2017. During this time span, the points exhibited an average velocity of 3.3 cm per year. The results of the PSI analysis found displacement at the same area as the GNSS control network. Longer-term monitoring of the site is required in order to diagnose the severity of the displacement.

Figure 5. PSI analysis of the site. The site where the displacement occurred is indicated by the red dot within the white perimeter of the Choirokoitia site.

V. CONCLUSIONS

PROTHEGO's case study of Choirokoitia, Cyprus provides an example of how to detect and analyze deformation phenomena for monitoring and predicting geo-hazards using InSAR ground motion data and field survey techniques to measure and document the extent of damage of the natural hazard on the cultural heritage site. The InSAR data, GNSS, total station and level were used to measure the micro-movements, while the UAV and photogrammetry are used for documentation purposes and 3D modeling comparison. There was a correlation between the geodetic techniques and the SAR images, as the PSI analysis and GNSS Control Network of the Choirokoitia site showed similar levels of displacement. This indicates the need for longer-term monitoring of the site to diagnose the severity of the geo-hazards. Local-scale monitoring data is the base for the development of geological and geotechnical modelling of the investigated sites, which will provide evolution models for the deformation processes affecting the heritage sites in order to recognize the best mitigation strategies and to evaluate the effectiveness of these actions for cultural heritage protection.

VI. ACKNOWLEDGEMENTS

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References

Agapiou, A., Hadjimitsis, D.G. and Alexakis, D.D. (2013). Development of an image-based method for the detection of archaeological buried relics using multi-temporal satellite imagery, *International Journal of Remote Sensing*, 34(16), pp. 5979-5996. DOI: 10.1080/ 01431161. 2013.803630.

Brimblecombe*,* P. (2000). Air pollution and architecture*,* past*,* present and future*. Journal of Architectural Conservation*. 6, pp. 30–46.

Burkhart, A., Cogliati, S., Schickling, A. and Rascher, U. (2014). A Novel UAV-Based Ultra-Light Weight Spectrometer for Field Spectroscopy. *Sensors Journal IEEE*, (14)1, pp. 62-67. doi10.1109/JSEN.2013.2279720

Canuti, P., Margottini, C., Fanti, R. and Bromhead, E. N. (2009). *Cultural heritage and landslides: research for risk prevention and conservation*. Landslides–Disaster Risk Reduction, pp. 401-433. Springer: Berlin Heidelberg.

Chen, F., Lin, H., Li, Z., Chen, Q and Zhou, J. (2012). I*nteraction between permafrost and infrastructure along the Qinghai–Tibet Railway detected via jointly analysis of C-band l-band small baseline SAR interferometry*. Remote Sensing and Environment, 123, 532–540.

Chen, F., Lin, H., Zhou, W., Hong, T. and Wang, G. (2013). *Surface deformation detected by ALOS PALSAR small baseline SAR interferometry over permafrost environment of Beiluhe section, Tibet Plateau, China*. Remote Sensing and Environment, 138, 10–18.

Cigna F., Del Ventisette C., Gigli G., Menna F., Agili F., Liguori V. and Casagli N. (2012). Ground instability in the old town of Agrigento (Italy) depicted by on site investigations and Persistent Scatterers data. Natural Hazards and Earth System Sciences, 12, pp. 3589-3603.

Cigna, F, Lasaponara, R, Masini, N, Milillo, P and Tapete, D. (2014). *Persistent Scatterer Interferometry Processing of COSMO-SkyMed StripMap HIMAGE Time Series to Depict Deformation of the Historic Centre of Rome, Italy*. Remote Sensing, 6(12), 12593-12618.

Colomina, I. and Molina, P. (2014). Unmanned aerial systems for photogrammetry and remote sensing: a review. *ISPRS Journal of Photogrammetry and Remote Sensing*, 92, pp. 79-97.

Crosetto M., Monserrat O., Iglesias R. and Crippa B. (2010). Persistent scatterer interferometry: Potential, limits and initial C- and X-band comparison. *Photogrammetric Engineering* and *Remote Sensing,* 76, pp. 1061–1069.

Ferretti, A., Fumagalli, A., Novali, F., Prati, C., Rocca F. and Rucci, A. (2011). A New Algorithm for Processing Interferometric Data-Stacks: SqueeSAR," *IEEE Transactions on Geoscience and Remote* Sensing, 49(9), pp. 3460-3470. doi: 10.1109/TGRS.2011.2124465

Fort, R., de Buergo, M. A., Gomez-Heras, M. and Vazquez-Calvo, C. (2006): (Eds.): *Heritage, Weathering and Conservation*, In: Proceedings of the International

Conference on Heritage, Weathering and *Conservation* (*HWC-2006*) 21-24 June 2006, Madrid, Spain.

Garziera, R., Amabili, M and Collini, L. (2007). *Structural health monitoring techniques for historical buildings.* In Proceedings of the 4th Pan-American Conference for Non-Destructive Testing, Buenos Aires, Argentina, 22–26 October 2007.

Glisic, B. and Inaudi, D. (2008). *Fiber Optic Methods for Structural Health Monitoring*. John Wiley and Sons: Hoboken, NJ, USA.

Gutiérrez, F. and Cooper, A. H.; (2002). Evaporite dissolution subsidence in the historical city of Calatayud, Spain: damage appraisal and prevention. *Natural Hazards*, 25(3), 259-288.

Haddad, N.A. (2011). From ground surveying to 3D laser scanner: A review of techniques used for spatial documentation of historic sites. *Journal of King Saud University,* 23, (2), pp. 109-118.

Hooper, A., Bekaert, D., Spaans, K. and Arıkan, M. (2012). Recent advances in SAR interferometry time series analysis for measuring crustal deformation. Tectonophysics, 514–517, 1-13, http://dx.doi.org/10.1016/j.tecto.2011.10.013.

Ioannides, M, Hadjiprocopis A., Doulamis N., Doulamis A., Protopapadakis Eft., Makantasis K., Santos P., Fellner D., Stork A., Balet O., Julien M., Weinlinger G., Johnson P. S., Klein M. and Fritsch D. (2013).; Online 4D Reconstruction using Multi-Images available under Open Access. I*SPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume II-5/W1, pp.169-174.

Kostrzewa, J., Meyer, W., Laband, S., Tere, W., Petrovich, P., Swanson, K. Sundra, C., Sener, W. and Wilmott, J. (2003). *Infrared microsensory payload for miniature unmanned aerial vehicles.* In: Proceedings of SPIE 5090, Unattended Ground Sensor Technologies and Applications, pp. 265, 2003.

Lo Brutto M., Garraffa A. and Meli P. (2014). UAV Platforms for Cultural Heritage Survey: First Results. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume II-5, 2014, pp. 227-234.

Margottini, C., Antidze, N., Corominas, J., Crosta, G. B., Frattini, P., Gigli, G., Giordan, D., Iwasaky, I. ,Lollino, G., Manconi, A., Marinos, P., Scavia, C., Sonnessa, A., Spizzichino, D. and Vacheishvili N. (2015). Landslide hazard, monitoring and conservation strategy for the safeguard of Vardzia Byzantine monastery complex. *Landslides*, 12(1), pp. 193–204. DOI: 10.1007/s10346-014-0548-z

Margottini C., Spizzichino D., Cigna F., Crosta G. B., Frattini P., Themistocleous, K. & Fernandez Merodo J. A. (2016) European UNESCO Cultural Heritage and Geo – Hazards: The PROTHEGO Project". In: Proceedings of the Fourth International Conference on Remote Sensing and Geo-information of Environment, 4-8 April, 2016, Paphos, Cyprus.

Margottini C., Spizzichino D., Leoni G., Bee E.J., Crosta G.B., Frattini P., Themistocleous K. and Fernandez Merodo J.A. (2018) Satellite Monitoring Applied to Natural Hazards and Cultural Heritage: The PROTHEGO Project. Sixth International Conference on Remote Sensing and Geo-information of Environment, 26-29 March, 2018, Paphos, Cyprus.

Novellino A., Harrison A., Bee E., Wang L., Hobbs P., Margottini C., Themistocleous K., Crosta G.B., and Fernandez Merodo J.A. (2018) Characterising and modelling geohazard susceptibility in the UNESCO World Heritage Site of the Derwent Valley Mills (UK). Geophysical Research Abstracts, Vol. 20, EGU2018-13316-1, 2018, EGU General Assembly 2018, Vienna, 8–13 April 2018.

Rohn, J., Ehret, D., Moser, M. and Czurda, K. (2005). Prehistoric and recent mass ;movements of the World Cultural Heritage Site Hallstatt, Austria. Environmental Geology, 47(5), pp. 702-714

Rosen P.A., Hensley S., Joughin I.R., Fuk K.L., Madsen S.N., Rodriguez E. and Goldstein, R. (2000). Synthetic aperture radar interferometry. *Proceedings of the IEEE*, 88(3), 88, pp. 333–382.

Ruffino, G. and Moccia, A., (2005). Integrated VIS_NIR Hyperspectral/thermal-IR Electro-optical Payl-oad System for a Mini-UAV. *American Institute of Aeronautics and Astronautics*, pp. 647-664.

Scholtz, A., Kaschwich, C. Kruger, A., Kufieta, K., Schnetter, P., Wilkens, C., Kruger, T. and Vorsmann, P. (2011). Development of a new multi-purpose UAS for scientific application. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38,149–154.

Silvestrou A. and Themistocleous K. (2018) Multi-critera Analysis Of UNESCO Sites In Cyprus: The Case Study of Choirokoitia. Sixth International Conference on Remote Sensing and Geo-information of Environment, 26-29 March, 2018, Paphos, Cyprus.

Tang, P., Chen, F. Zhu, X. & Zhou, W. (2016). Monitoring Cultural Heritage Sites with Advanced Multi-Temporal InSAR Technique: The Case Study of the Summer Palace. *Remote Sensing*, 8, pp. 432 doi:10.3390/rs8050432.

Themistocleous, K., Agapiou, A., King, H.M., King, N. and Hadjimitsis, D.G. (2014a). *More Than a Flight: The Extensive Contributions of UAV Flights to Archaeological Research - The Case Study of Curium Site in Cyprus*. In: Proceedings of Progress in Cultural Heritage: Documentation, Preservation, and Protection. 5th International Conference, EuroMed 2014, Limassol, Cyprus. Springer LNCS 8740, EuroMed2014 Conference, 396-409.

Themistocleous, K., Agapiou, A., Cuca, B. and Hadjimitsis, D.G. (2014b). *3D Documentation Of Cultural Heritage Sites.* In: Proceedings of Progress in Cultural Heritage: Documentation, Preservation, and Protection. 5th International Conference, EuroMed 2014, Limassol, Cyprus, Springer LNCS 8740, EuroMed2014 Conference.

Themistocleous, K., Agapiou, A., Alexakis, D., Cuca, B. and Hadjimitsis, D.G. (2014c). *Lessons learnt from using UAVs in Cyprus: landscapes applications*. In: Proceedings of the Archland UAV Conference 2014, 23-25 May, Berlin, Germany.

Themistocleous K., Agapiou A., Cuca, B. and Hadjimitsis, D.G. (2015a). *Unmanned Aerial Systems And Spectroscopy For Remote Sensing Applications In Archaeology*. In: Proceedings of the 36th International Symposium of Remote Sensing and Environment. (ISRSE-36), 11-15 May, 2015, Berlin Germany.

Themistocleous, K., Ioannides, M., Agapiou, A., Hadjimitsis, D.G. (2015b). *The Methodology Of Documenting Cultural*

Heritage Sites Using Photogrammetry, UAV And 3D Printing Techniques: The Case Study Of Asinou Church In Cyprus. In: Proceedings of the Third International Conference on Remote Sensing and Geoinformation of Environment, 16-19 March, 2015.

Themistocleous K., A. Agapiou, deHoop M., Mayor A.G., Rietkerk M., Dekker S.C. and Hadjimitsis D.G. (2015c). T*he Use of UAV to Document Sloping Landscapes to Produce Digital Elevation Models To Examine Environmental Degradation.* In: Proceedings of the Third International Conference on Remote Sensing and Geo-information of Environment, 16-19 March, 2015, Paphos, Cyprus.

Themistocleous K., Agapiou, A. and Hadjimitsis, D.G. (2016a) Experiencing Cultural Heritage Sites Using 3D Modeling for the Visually Impaired". In: Proceedings of Euromed 2016: Digital Heritage, Progress in Cultural Heritage: Documentation, Preservation, and Protection, Lecture Notes in Computer Science, Vol. 10059, 171-177, 31 October - 4 November, 2016 Nicosia Cyprus

Themistocleous K. (2017) The Use Of UAVs To Monitor Archeological Sites: The Case Study of Choirokoitia within the PROTHEGO Project. Fifth International Conference on Remote Sensing and Geo-information of Environment, 20-23 March, 2017, Paphos, Cyprus.

Themistocleous, K., Danezis, C., Mendonidis, E. and Lymperopoulou, E. (2017a). Monitoring ground deformation of cultural heritage sites using UAVs and geodetic techniques: the case study of Choirokoitia, JPI PROTHEGO project. Proceedings of the SPIE Remote Sensing Conference Vol. 10428, 104280Q, Earth Resources and Environmental Remote Sensing/GIS Applications VIII,11-14 September, 2017. Warsaw, Poland. doi: 10.1117/12.2279478.

Themistocleous, K., Danezis, C. and Mendonidis E. (2017b). Best Practices For Monitoring, Mitigation and Preservation of Cultural Heritage Sites Affected By Geo-Hazards (in Greek). Euromed 2017 conference, 1-3 December, 2017, Volos Greece.

Themistocleous, K., Danezis, C. & Mendonidis E. (2017c). Best Practices For Monitoring, Mitigation and Preservation of Cultural Heritage Sites Affected By Geo-Hazards (in Greek). Euromed 2017 conference, 1-3 December, 2017, Volos Greece.

Themistocleous K., Michaelides S. and Hadjimitsis D.G. (2018). The Integrated Use of Space Technologies, UAVs and Field Measurements Intended for Cultural Heritage in Cyprus. Geophysical Research Abstracts Vol. 20, EGU2018-5282-1, 2018 EGU General Assembly 2018, Vienna, 8–13 April 2018.

Themistocleous K. (2018) Local Monitoring Techniques for Cultural Heritage Sites Affected By Geo-Hazards. Sixth International Conference on Remote Sensing and Geo-information of Environment, 26-29 March, 2018, Paphos, Cyprus.

UNESCO World Heritage List "Choirokoitia"<http://whc.unesco.org/en/list/848>. (1 March, 2016).

Zhou W., Chen F. and Guo, H. (2015). Differential Radar Interferometry for Structural and Ground Deformation Monitoring: A New Tool for the Conservation and Sustainability of Cultural Heritage Sites. *Sustainability (Basel),* ISSN 2071-1050, doi:10.3390/su7021712, pp.1712-1729.