The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-2-2023
29th CIPA Symposium "Documenting, Understanding, Preserving Cultural Heritage:
Humanities and Digital Technologies for Shaping the Future", 25–30 June 2023, Florence, Italy

COSMO-SKYMED: A SATELLITE TOOL FOR MONITORING CULTURAL HERITAGE

M. Virelli [1 *], A. Coletta [1], D. Tapete [1 *], F. Cigna [2]

[1] Italian Space Agency, ASI, 00133 Rome, Italy – (maria.virelli, alessandro.coletta, deodato.tapete)@asi.it
[2] Institute of Atmospheric Sciences and Climate, ISAC, National Research Council, CNR, 00133 Rome, Italy - f.cigna@isac.cnr.it

KEY WORDS: Cultural heritage, Built heritage, Archaeological sites, COSMO-SkyMed, Synthetic Aperture Radar, Satellite, Monitoring.

ABSTRACT:

COSMO-SkyMed is the flagship Synthetic Aperture Radar (SAR) satellite constellation of the Italian Space Agency (ASI) that, among the many civilian applications for which it was originally conceived, is nowadays successfully exploited for cultural heritage applications. Current capabilities offered by both the First and Second Generations satellites are reviewed in light of the experience undertaken by ASI through data exploitation initiatives with scientific and commercial users, and more importantly in the framework of institutional projects and cooperation agreements such as those with the Colosseum Archaeological Park and the Italian Ministry of Culture (MiC). The interferometric nature of COSMO-SkyMed SAR acquisitions is the key feature exploited in structural and ground deformation monitoring of monuments and historical buildings, so as the constellation is currently the essential Earth Observation asset supporting MiC's Extraordinary Plan of Monitoring and Conservation of Immovable Cultural Heritage. Further applications that could be enabled by COSMO-SkyMed data are explored through internal ASI research activity, such as the use of high resolution Digital Elevation Models (DEM) for topographic surveying of archaeological tells and condition assessment to estimate the impact due to natural and anthropogenic threats (e.g. looting, agriculture, destruction). Finally, current perspectives towards operational use and greater user uptake of COSMO-SkyMed for purposes of scientific downstream are opened by the new ASI programme Innovation for Downstream Preparation for Science (I4DP_SCIENCE).

1. INTRODUCTION

Satellite data are nowadays an established means for the study and conservation of cultural heritage. While in most cases satellite images from optical sensors are exploited, more heritage users have been approaching Synthetic Aperture Radar (SAR) technologies and testing multi-band, multi-polarization and very high spatial resolution data. Of the several SAR-based observing systems, the COSMO-SkyMed constellation of the Italian Space Agency (ASI) is the most suited for cultural heritage monitoring (Tapete and Cigna, 2017, 2019; Figure 1), thanks to its huge archives of long time series of SAR data collected across the globe, high spatial resolution and weekly revisit time (Virelli et al., 2014). The present paper demonstrates how COSMO-SkyMed has been impactful for boosting applications in cultural heritage monitoring, and thus is a resource for heritage bodies and institutions to support conservation and ordinary maintenance.

2. COSMO-SKYMED CONSTELLATION

In 2003 ASI and the Italian Ministry of Defence (MoD) commissioned and funded the COSMO-SkyMed (COnstellation of small Satellites for Mediterranean basin Observation) dual system (civil and military), which currently represents the largest Italian investment in the field of Earth observation (Caltagirone et al., 2014).
Initially, the system consisted in the First Generation constellation (CSK) of four Low Earth Orbit mid-sized satellites, each equipped with a multi-mode high-resolution SAR operating at X-band (3.1 cm wavelength). CSK satellites were launched between June 2007 and November 2010, thus allowing the constellation to be fully operational since 2011 (Figure 2). The First Generation was then upgraded with the Second Generation of COSMO-SkyMed satellites (CSG). The first two CSG satellites were launched on 18 December 2019 and 1 February 2022, respectively, while the third and fourth will be launched in the next years.

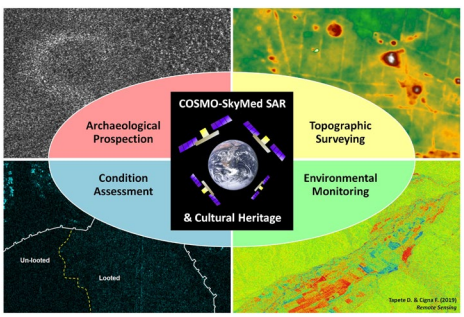

Figure 1. COSMO-SkyMed application domains for cultural heritage (from Tapete and Cigna, 2019).

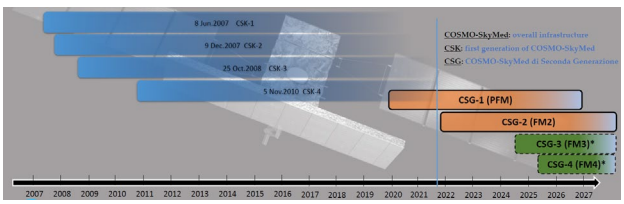

Figure 2. Timeline of COSMO-SkyMed First and Second Generations satellites.

* Corresponding author

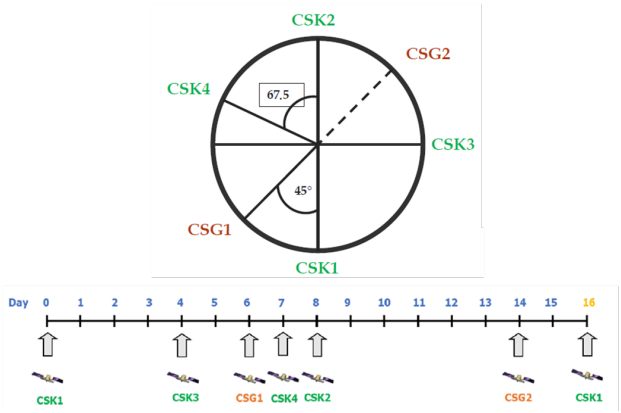

Figure 3. COSMO-SkyMed orbital configuration.

Figure 3 shows the orbital configuration of the satellites before CSK-3 was deorbited starting from 1 May 2022, and the associated wide range of revisit times that can be achieved over the same place on Earth's surface.

As discussed by Tapete and Cigna (2019), of all the imaging modes offered by the CSK satellites, Enhanced Spotlight data in single polarization are the most suited for local/site-scale investigations and fine mapping in cultural heritage sites, while StripMap Himage mode provides the best trade-off between high spatial resolution (less than 5 m) and areal coverage. With CSG this is even more corroborated, given that Spotlight-2B and 2C achieves 0.6 m × 0.6 m and 0.8 m × 0.8 m, respectively, both StripMap Himage and Spotlight-2B/2C images can be collected in either single or dual polarization, and a full quad-polarization mode has been added.

Furthermore, the very high temporal frequency of observation, which is peculiar of COSMO-SkyMed, is highly advantageous to assess the impact on monuments, historical buildings and archaeological heritage caused by natural and anthropogenic hazard events in case of emergencies, as well as during armed conflicts. In these situations, imagery acquired timely and with short revisiting time is an asset. It also proves crucial to undertake routine monitoring of processes that change quickly and need to be tracked dynamically. No other currently active SAR mission can offer this capability or similar agility to increase or decrease the revisiting time during the acquisition of the time series.

3. DATA EXPLOITATION FOR INSTITUTIONAL AND DOWNSTREAM APPLICATIONS

In 12 years of activity of COSMO-SkyMed, ASI has supported various projects aimed at monitoring cultural heritage, either UNESCO World Heritage Sites (WHS) or scheduled monuments. Additionally, ASI has undertaken several research studies to unveil the capabilities of the COSMO-SkyMed data.

The earliest experiences include the "World HEritage monitoring by REmote sensing (WHERE)" (Carlucci et al., 2012), activated in the frame of the second call with the Italian Ministry of Culture (MiC) dedicated to national small and medium-sized enterprises (SMEs), co-financed by ASI. To demonstrate a satellite-based operational service for the short-term monitoring of UNESCO WHS and sites of archaeological interest in urban areas, WHERE developed applications to aid methods and procedures currently in use by creating a low cost technical-scientific support device, thus providing the interested administrations with a useful tool for monitoring sites for conservation purposes.

Enabling user-driven services (also in the context of international programmes) is a key objective of ASI's institutional mandate. In this respect, the ArTeK project, supported in the frame of ARTES 20 IAP programme of the European Space Agency, delivered the following service portfolio: Safeguard Support; On-site Monitoring; and Site Management Support & Mobile Fruition. COSMO-SkyMed imagery was exploited not only for identification of areas potentially in danger (e.g. in Villa Adriana WHS as part of an integrated protocol with in situ sensors, such as crack-meters, GNSS receivers, inclinometers, accelerometers), but also to address the conservation of underwater archaeological heritage due to volcanic motions in Baia, southern Italy, and ship traffic in Mediterranean sites (Benenati et al., 2017).

Further proof that COSMO-SkyMed is now exploited by national institutional stakeholders as a tool for monitoring cultural heritage is provided by the Pompeii project and the collaboration with the Colosseum Archaeological Park. As part of the collaborative effort between different institutions and professionals to address the serious conservation issues that affected Pompeii, COSMO-SkyMed interferometric products were exploited to detect ground deformation of potential concern. The interferometric analysis was effective owing to its ability to provide a large number of strain measurements on the target structures (Costantini et al., 2016), and confirmed the added-value of COSMO-SkyMed for preventive diagnostic surveys of the structural health of archaeological ruins.

3.1 The project with the Colosseum Archaeological Park

A few years ago, the Colosseum Archaeological Park initiated a dedicated monitoring project (that started in a systematic way only in 2018) covering the whole extent of the park. This project was inspired by the desire to build a sustainable system of protection and conservation, then allowing a proper tourism valorisation. With these objectives in mind, the Colosseum Archaeological Park has developed a static and dynamic monitoring project, consisting of five fundamental levels of activities: (i) a database of all the historical data of the monuments, together with the existing graphic and photographic documentation (namely digital documentation archive); (ii) visual monitoring carried out by teams of technicians dedicated to the inspection and control of monuments, also thanks to a dedicated app that will allow to send data to the central system; (iii) satellite monitoring (historical analysis of the satellite data) going directly into the system and analysed in order to monitor possible ground deformation; (iv) in situ monitoring from traditional geotechnical instruments; (v) experimental activities, such as the use of Heritage Building Information Modeling (HBIM) in the archaeological field, aimed at monitoring by diagnostic instruments (Russo et al., 2023).

The above levels make very evidently how satellite monitoring is given the same degree of importance as the other monitoring components that mostly rely on consolidated and traditional techniques for heritage building surveying and monitoring. Satellite data therefore contribute to a multi-parameter system of permanent control of the entire archaeological area, with associated indicators of the level of risk. The overall project objective is to allow planning, in an effective and timely manner, of the necessary interventions for both ordinary and extraordinary maintenance based on objective, reliable, reproducible and interoperable data, thus providing not only an operational tool, but also a management system for the Park with a better use of its financial resources.

The Park Management considered fundamental the use of satellite historical analysis of the archaeological area, which was carried out for the period 2011-2018 (Figure 4). The full time series of COSMO-SkyMed StripMap Himage scenes collected over the central archaeological area of Rome were

provided by ASI and then processed on commission by e-GEOS with Interferometric SAR (InSAR) techniques, namely the Persistent Scatterer Pairs (PSP-IFSAR) method (Costantini et al., 2014). The PSP-IFSAR technique allows estimation of ground displacements over large areas with millimetric precision, at the full spatial resolution provided by COSMO-SkyMed StripMap Himage mode, thus suiting the single building scale required by this type of high-definition structural monitoring.

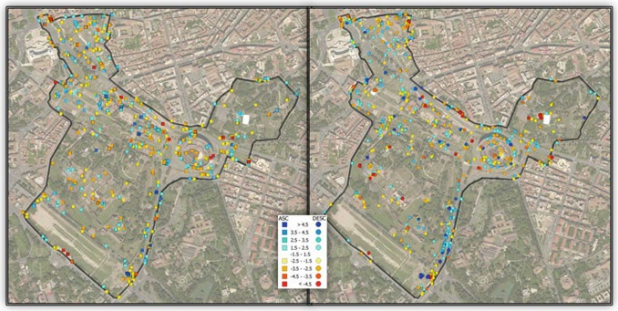

Figure 4. Spatial distribution of ground and structural deformation points as retrieved by e-GEOS using the PSP-IFSAR technique for the period March 2011–2018 with COSMO-SkyMed data (from Russo et al., 2023).

The step forward achieved at the Colosseum compared to previous experiences was that the interferometric outputs were included in the WebAPP system (namely SyPEAH; Della Giovampaola, 2021) developed by the Archaeological Park itself as the heritage body's tool for an effective activity of programmed conservation of cultural heritage with particular regard to archaeological structures. COSMO-SkyMed data were ingested into the institutional user workflow, instead of remaining a dataset interpreted externally to the decision-making process, as unfortunately frequently happens in research-focused studies or consultancies. Figure 5 shows the implementation of historical deformation analysis over the Flavian Amphitheatre. The outcome of the experimentation was the development of a system for ground validation of satellite data, in order to define a protocol that could be replicated on a larger scale, given the extent of the whole central archaeological area of Rome.

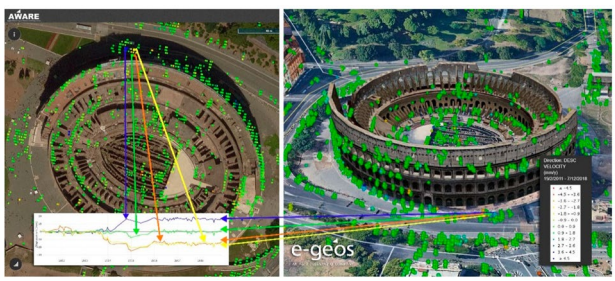

Figure 5. Implementation of historical deformation analysis over the Flavian Amphitheatre, Colosseum Archaeological Park, Italy, whose geometric and material characteristics made it particularly suitable for structural monitoring with interferometric processing and analysis (COSMO-SkyMed data processed by e-GEOS) (from Della Giovampaola, 2021).

3.2 Extraordinary Plan of Monitoring and Conservation of Immovable Cultural Heritage

At national level, the most recent institutional collaboration that ASI has initiated in this field of application has been signed with MiC in February 2023. The ASI-MiC agreement establishes that the two Parties cooperate in the implementation of the work phases of the "Extraordinary Plan of Monitoring and Conservation of Immovable Cultural Heritage" (*Piano Straordinario di Monitoraggio e Conservazione dei Beni Culturali Immobili*). The Plan defines the criteria to identify the properties that are to be monitored and where conservation measures need to be made, alongside the required priority order of the inspections and controls, also based on specific indices of territorial hazard and the individual vulnerability of each property. The Plan also aims to define the systems for instrumental control to exploit and the implementation modalities of safety, conservation and safeguard measures (MiC, 2023).

As a further proof that satellite technologies are nowadays well embedded in the heritage management practice at Italian institutional levels, the Plan (MiC, 2023):

- Matches the requirements expressed by the national users in charge of monitoring and conservation of cultural heritage in the framework of consultancy activities of users of the National Copernicus User Forum;
- Contributes to the definition of the technical requirements for the national operational services of territorial monitoring that will be provided through the implementation of the Space Economy – Mirror Copernicus Program;
- Foresees the harmonisation of existing laws concerning satellite monitoring, in the framework of the activities of the "Earth Observation" Working Group of the Italian Government Presidency of the Council of Ministers (PCM).

The first of the five levels through which the Plan is developed focuses on the identification of the data needed for monitoring and acquisition/return model. The Plan therefore promotes the integration of Earth observation and remote sensing data collected from different observation platforms (satellites, airborne, photographic) with territorial surveys and in situ measurements. Satellite products are conceived as the first element of an "observation chain", allowing preliminary identification of critical areas (anomalies) where detail investigations are further undertaken.

In this context, over 2022, ASI provided MiC and its partners with access to long time series of COSMO-SkyMed first and second generation satellite data that were mostly collected over several monumental and archaeological areas in Italy via the Map Italy project since 2011 and 2021, respectively. The wide portfolio of sites includes: Venice and its Lagoon, Pisa, Ferrara, Padua, Verona, Rieti, Pienza, Volterra, Civita di Bagnoregio, Aurelian Walls in Rome, Pilgrim's Way - Via Francigena (south trait within the Municipality territory of Rome), Phlegraean Fields Archaeological Park, Paestum and Velia, Roman Villa in Piazza Armerina, Archaeological Park of Baratti and Populonia, Submerged Park in Baia, Ancient harbour of Classe and Ravenna. COSMO-SkyMed data were then processed using Persistent Scatterer Interferometry (PSI) and change detection techniques, also in synergy and continuation with existing projects and recent initiatives (see for example Caprino et al., 2023; Raspini et al., 2023). The results are currently analysed by the various research teams involved in the Plan, and the perspective is that ASI will support MiC not only with the further provision of COSMO-SkyMed data, but also with the definition of guidelines and protocols for integration of the different monitoring technologies and calibration of satellite monitoring techniques, alongside an integrated satellite and in situ instrumental monitoring.

4. RESEARCH ON NOVEL APPLICATIONS

The experiences described above rely on well established SAR processing methods and analytical methodologies. Whereas, another key objective of the ASI's roadmap in COSMO-SkyMed data exploitation across the user community is also to stimulate the use of imaging modes, product types and technical properties that are still less used. On one side, the new capabilities brought by CSG satellites to address applications in the field of cultural heritage are yet to be tested, and there are no literature or developed use-cases in this regard. On the other side, recent research has taken full advantage of CSK data, either from the wealth of archive imagery (mainly from the Background Mission) or from bespoke observation campaigns, to prove that other applications can be enabled.

4.1 Archaeological surveying with high-resolution DEMs

For example, COSMO-SkyMed DEMs generated at 10-m posting from purposely collected 1-day tandem pairs were proved effective not only to support digital survey of archaeological mounds and deposits in arid to semi-arid environments (e.g. in the Middle East) to improve knowledge of cultural landscapes, but also to monitor, through regular observation, the impacts due to anthropogenic disturbance (e.g., urbanization, road and canal constructions or ploughing). Figure 6 and Figure 7 show two examples of tells in the Wasit Governorate in Iraq (Tapete et al., 2021), the location and presence of which were known from field surveys. In the first case (Figure 6), the topographic pattern and associated profile extracted from the COSMO-SkyMed StripMap Himage DEM complement the clear signals in the visible, NIR, and radar bands that already suggested the presence of a mound with 4 m height and over 200 m diameter. These morphological properties match with those typical of archaeological tells. On the contrary, in the second case (Figure 7), no evident surface mark or contrast in multispectral bands or distinctive radar backscatter versus the surrounding soil is found in satellite imagery. Therefore, the pattern identified in the COSMO-SkyMed DEM becomes essential to reveal the presence of the mound (Figure 7d). Additionally, the asymmetrical shape of the topographic profile (Figure 7e) suggests that the mound topography may have been partially flattened and altered over time. COSMO-SkyMed DEMs therefore proved sufficiently selective to discriminate instances where archaeological tells are well preserved and where they are altered and at risk of vanishing.

By means of these DEMs and through amplitude change detection techniques as per the methodology by Tapete and Cigna (2019), an overall map of the archaeological tells was achieved for the sub-districts south-east of Baghdad, including Al-Zubaidiya and Al-Shehamiya (Figure 8a; Tapete et al., 2021). Each entry was assigned an 'archaeological reliability' score according to a five-tiered scale from 1 (very low) to 5 (very high). Reliability was defined as the level of likelihood of the trace to have an anthropogenic origin. The score was assigned based on the number of repeated identifications over multiple examined sources. As a higher archaeological reliability would correspond to priority for the location being inspected during the ground-truth phase, this value was translated into a 'Priority' value. The map in Figure 8a clearly highlights a concentration of clusters of priority 5 tells at larger diameters in the south-eastern portion of the AOI. Such type of maps are helpful to archaeologists as one of the foundational evidence-base datasets to infer settlement patterns of ancient civilizations across a wide region.

At the same time, maps of condition assessment can be issued for each category of natural or anthropogenic threat, such as looting (Figure 8b). In particular, the analysis in Wasit highlighted that 42% and 38% of the identified looted sites are classified as very high to high priority, respectively (Figure 9d). The possibility of these hypothetical archaeological sites to genuinely be tells is demonstrated by the existence of looting traces in their proximity, as it is likely that the archaeological potential of the sites were known to local traffickers.

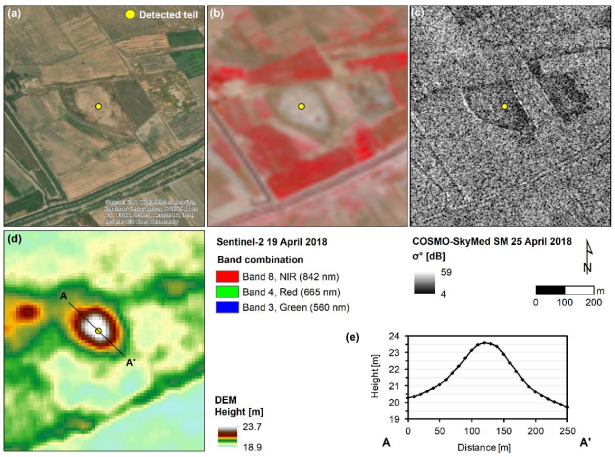

Figure 6. Detection of well-preserved archaeological tell through combination of (**a**) optical imagery, (**b**) Copernicus Sentinel-2 multispectral false-coloured composite, COSMO-SkyMed (**c**) SAR radar backscatter image, and (**d**) DEM with (**e**) height profile drawn along A-A' section. COSMO-SkyMed® Products ©ASI, 2018. All rights reserved. Contains Copernicus Sentinel-2 data, 2018 (from Tapete et al., 2021).

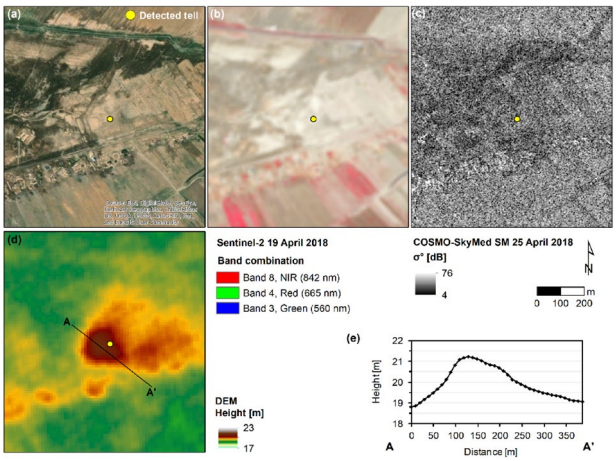

Figure 7. Detection of flattened and altered archaeological tell through combination of (**a**) optical imagery, (**b**) Copernicus Sentinel-2 multispectral false-coloured composite, COSMO-SkyMed (**c**) SAR radar backscatter image, and (**d**) DEM with (**e**) height profile drawn along A-A' section. COSMO-SkyMed® Products ©ASI, 2018. All rights reserved. Contains Copernicus Sentinel-2 data, 2018 (from Tapete et al., 2021).

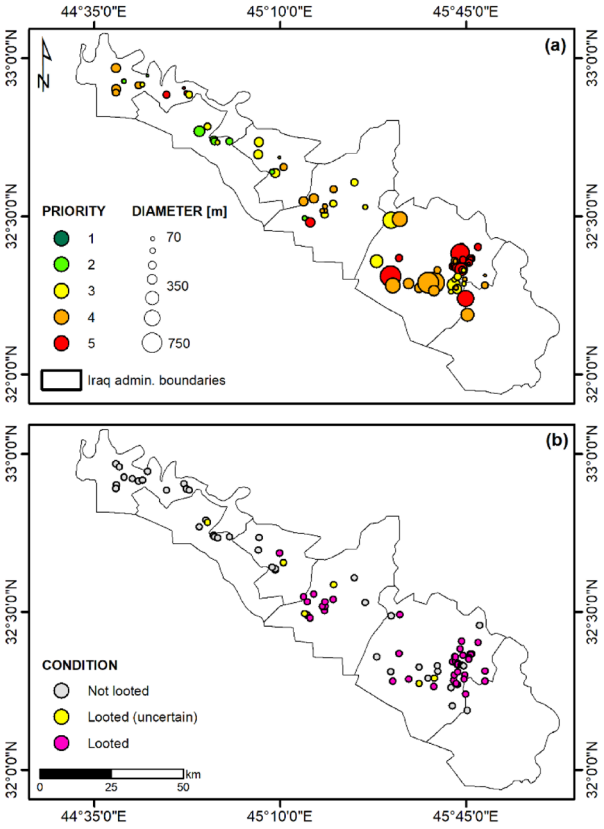

Figure 8. Spatial distribution of mapped tells in Al-Zubaidiya and Al-Shehamiya sub-districts, Wasit (Iraq): (**a**) by priority and their diameter (expressed in meters); and (**b**) by condition as assessed through visual interpretation of evidence of looting in satellite imagery (from Tapete et al., 2021).

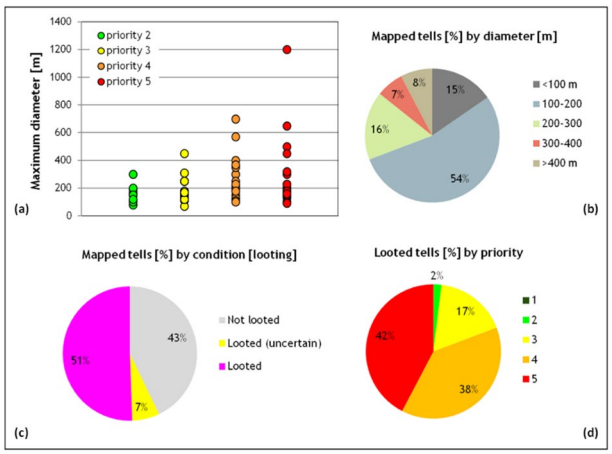

Figure 9. Statistics of the mapped tells by: (**a**) size (i.e., maximum diameter) vs. archaeological priority, (**b**) size class, (**c**) condition (i.e., as assessed through visual interpretation of satellite imagery), and (**d**) looting evidence vs. archaeological priority (from Tapete et al., 2021).

The methodology is geographically exportable, as proved by the implementation undertaken by Tapete and Cigna (2022) in Al-Ahrar, Al-Nu'maniya, also in integration with other high-resolution satellite DEMs. Figure 10 shows the spatial distribution of the mapped tells by the mostly impacting threats due to anthropogenic actions. The latter are defined accounting for the standard list of primary threats and secondary factors affecting the Outstanding Universal Value of UNESCO's World Heritage properties (UNESCO, 2023), as well as the three-tier framework of risk to archaeological sites implemented by Zaina (2019) in a neighbouring region in southern Iraq. The results therefore demonstrate how these maps and statistics can be generated as operational products addressing specific investigation needs.

From a downstream point of view, if such maps and statistics were produced in the framework of a flow by which the information extracted from satellite products could be directly embedded into the daily workflow of local stakeholders and authorities, they could directly offer a monitoring tool and be impactful on informing the actions to safeguard cultural heritage.

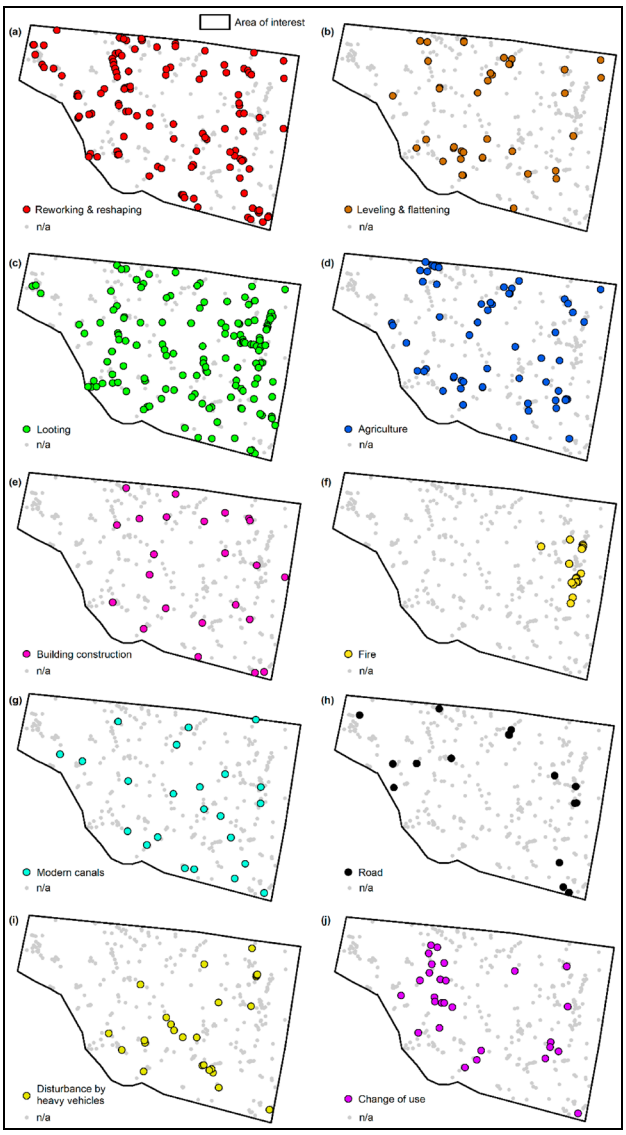

Figure 10. Spatial distribution of the mapped tells in Al-Ahrar, Al-Nu'maniya, Wasit (Iraq), by the mostly impacting threats due to anthropogenic actions: (**a**) reworking and reshaping, (**b**) leveling and flattening, (**c**) looting, (**d**) agriculture, (**e**) building construction, (**f**) fire, (**g**) modern canals, (**h**) road, (**i**) disturbance by heavy vehicles, and (**j**) change of use (from Tapete and Cigna, 2022).

5. CONCLUSIONS AND FUTURE PERSPECTIVES

The use-cases and institutional collaborations described in this paper prove how COSMO-SkyMed is a technological resource for ordinary monitoring and preventive conservation of cultural heritage, especially for structural monitoring by means of interferometric techniques. Demonstration and (pre-)operational projects, also in collaboration with end-users and companies, have stimulated the development of products and services in the frame of a full value-adding chain (from developers to end-users).

While on one side COSMO-SkyMed data are becoming an established resource to complement other datasets, remote sensing and in situ instrumental techniques in national heritage bodies' workflows, and thus are making impact on conservation policies and plans, on the other side ongoing research is widening the spectrum of applications in the field of cultural heritage, also for implementation abroad and at international level.

To further invest in technological transfer and the development of downstream applications, at the end of 2021 ASI also launched a new programme called "Innovation for Downstream Preparation (I4DP)", devoted to the main categories of users of satellite technologies, i.e. scientific, commercial and public administration. I4DP aims to demonstration development (through use-case and pilot projects) of innovative added-value services based on the use of Telecommunications (TLC), Navigation (NAV) and Earth Observation (EO) satellite systems, also mutually combined in a synergistic way and, whenever possible, integrated with non-spatial data and services, in order to prepare new generation downstream services and promote the full exploitation of national and European space systems, either already operational or under development.

To this purpose, "I4DP for Science" (I4DP_SCIENCE) is addressed to the scientific user community, and aims to capitalize the algorithm legacy developed in the past years during R&D projects and prepare the "scientific downstream". In space agencies' jargon, the latter term refers to the (pre-)operational exploitation of state-of-the-art processing and analytical workflows of TLC/EO/NAV data that have been designed, tested, validated and demonstrated by researchers and academia to formerly answer a specific technical-scientific question, and are brought to a development and engineered stage so as to generate end-use or value-added products (Tapete and Coletta, 2022).

I4DP_SCIENCE is implemented through a series of thematic "calls for ideas" that are regularly opened by ASI to collect project proposals from Italian Universities and Public Research Bodies in close cooperation with and engaging end-users and stakeholders. Safeguard of environment, cultural heritage and national landscape is among the key application domains covered by I4DP_SCIENCE. In this regard, both the first two calls that were launched in 2022 – on the themes "Sustainable Cities" and "Agriculture and Sustainable Use of Water Resources", respectively – included application domains related to cultural heritage and impact on rural and urban landscapes. The programme will last until 2026 and cultural heritage will remain one of the themes/application domains that will be explored, and where the capabilities of COSMO-SkyMed as a tool for monitoring cultural heritage will be certainly strengthened and disseminated.

ACKNOWLEDGEMENTS

Activities presented in this paper were undertaken in the framework of (in order): the Project of Colosseum Archaeological Park and the Italian Network of Archaeological Parks; the Extraordinary Plan of Monitoring and Conservation of Immovable Cultural Heritage funded by the Ministry of Culture (MiC) and the ASI – MiC cooperation agreement n. 2023-2-Q.0; internal ASI research based on COSMO-SkyMed® Products, ©Italian Space Agency (ASI), delivered under a license to use by ASI (Projects "Multi-SAR" and "LARICI", led by Deodato Tapete, and "BigSAR" led by Francesca Cigna); ASI's programme "Innovation for Downstream Preparation (I4DP)" under the Italian Government Presidency of the Council of Ministers (PCM)'s funding ex art. 1, c. 254, Law 160/2019, ASI – PCM agreement 27 December 2021.

REFERENCES

Benenati, L., Dore, N., Bernardi, L., Monteleone, A., 2017: ArTeK – Sistema di monitoraggio con COSMO-SkyMed e gestione dei Beni Culturali al servizio di gestori e visitatori. *ASI workshop "La Missione COSMO-SkyMed: Stato dell'Arte, Applicazioni e Prospettive Future"*, ASI, 13-15 November 2017. bandiasi.almaviva.it/it/eventi/convegni/decennale-cosmo-skymed (19 December 2022).

Caltagirone, F. *et al.*, 2014. The COSMO-SkyMed dual use earth observation program: Development, qualification, and results of the commissioning of the overall constellation. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* 7, 2754–2762. doi.org/10.1109/JSTARS.2014.2317287

Caprino, A., Bonaldo, G., Lorenzoni, F., da Porto, F., 2023. Application of Multi-Temporal InSAR (MT-InSAR) for structural monitoring: the case study of Scrovegni Chapel in Padova. *Procedia Structural Integrity*, 44, 1578-1585. doi.org/10.1016/j.prostr.2023.01.202.

Carlucci, R., Di Iorio, A., Folegani, M., Marsella, M., Monteleone, A., Mantovani, S., Placidi, A., Straccia N., 2012: World HEritage monitoring by Remote sEnsing (WHERE). *Atti 16a Conferenza Nazionale ASITA*, 6-9 November 2012, Vicenza, Italy, 375-382. ISBN 978-88-903132-7-1.

Costantini, M., Falco. S., Malvarosa, F., Minati, F., Trillo, F., Vecchioli, F., 2014. Persistent scatterer pair interferometry: approach and application to COSMO-SkyMed SAR data. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, 7(7), 2869–2879. doi.org/10.1109/JSTARS.2014.2343915.

Costantini, M., Francioni, E., Paglia, L., Minati, F., Margottini, C., Spizzichino, D., Trigila, A., Iadanza, C., De Nigris, B., 2016: PSP SAR interferometry monitoring of ground and structure deformations in the archeological site of Pompeii. *EGU General Assembly 2016*, 17-22 April 2016, Vienna, Austria, Geophysical Research Abstracts, Vol. 18, EGU2016-15312-2.

Della Giovampaola, I., 2021. SyPEAH: The WebAPP System for Protection and Education to Archaeological Heritage in the Parco Archeologico del Colosseo. *Geosciences*, 11(6), 246. doi.org/10.3390/geosciences11060246.

MiC (Ministero della Cultura), 2023. Piano straordinario di monitoraggio e conservazione dei beni culturali immobili. uss-sisma2016.cultura.gov.it/piano-straordinario-di-monitoraggio-e-conservazione-dei-beni-culturali-immobili/ (30 April 2023).

Raspini, F., *et al.*, 2023. The Potential of Satellite Interferometry for Geohazard Assessment in Cultural Heritage Sites. In: El-Qady, G.M., Margottini, C. (eds) *Sustainable Conservation of UNESCO and Other Heritage Sites Through Proactive Geosciences*. Springer Geology. Springer, Cham, 587–595. doi.org/10.1007/978-3-031-13810-2_30.

Russo, A., Della Giovampaola, I., Spizzichino, D., Leoni, G., Coletta, A., Virelli, M., 2023. The Project of Parco Archeologico Del Colosseo and the Italian Network of Archaeological Parks: From Satellite Monitoring to Conservation and Preventive Maintenance Policies. In: El-Qady, G.M., Margottini, C. (eds.) *Sustainable Conservation of UNESCO and Other Heritage Sites Through Proactive Geosciences*. Springer Geology. Springer, Cham, 659-678. doi.org/10.1007/978-3-031-13810-2_34.

Tapete, D., Cigna, F, 2017. Trends and perspectives of space-borne SAR remote sensing for archaeological landscape and cultural heritage applications. *Journal of Archaeological Science: Reports*, 14C, 716-726. doi.org/10.1016/j.jasrep.2016.07.017.

Tapete, D., Cigna, F., 2019. COSMO-SkyMed SAR for Detection and Monitoring of Archaeological and Cultural Heritage Sites. *Remote Sensing*, 11(11), 1326. doi.org/10.3390/rs11111326.

Tapete, D., Cigna, F., 2022. Detection, Morphometric Analysis and Digital Surveying of Archaeological Mounds in Southern Iraq with CartoSat-1 and COSMO-SkyMed DEMs. *Land*, 11(9), 1406. doi.org/10.3390/land11091406.

Tapete, D., Coletta, A. 2022. ASI's roadmap towards scientific downstream applications of satellite data. *EGU General Assembly 2022*, Vienna, Austria, 23–27 May 2022, EGU22-5643. doi.org/10.5194/egusphere-egu22-5643.

Tapete, D., Traviglia, A., Delpozzo, E., Cigna, F., 2021. Regional-scale systematic mapping of archaeological mounds and detection of looting using COSMO-SkyMed high resolution DEM and satellite imagery. *Remote Sensing*, 13(16), 3106. doi.org/10.3390/rs13163106.

UNESCO, 2023. UNESCO World Heritage Centre-List of Factors Affecting the Properties. whc.unesco.org/en/factors/ (30 April 2023).

Virelli, M., Battagliere, M.L., Coletta, A., 2014. ASI COSMO-SkyMed mission overview and data exploitation. *IEEE Geoscience and Remote Sensing Magazine*, 2(2), 64-66. doi.org/10.1109/MGRS.2014.2317837.

Zaina, F., 2019. A Risk Assessment for Cultural Heritage in Southern Iraq: Framing Drivers, Threats and Actions Affecting Archaeological Sites. *Conserv. Manag. Archaeol. Sites*, 21(3), 184–206. doi.org/10.1080/13505033.2019.1662653.