International Journal of Applied Earth Observations and Geoinformation 112 (2022) 102907

Contents lists available at ScienceDirect

International Journal of Applied Earth Observations and Geoinformation

journal homepage: www.elsevier.com/locate/jag

The role of imaging radar in cultural heritage: From technologies to applications

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ARTICLE INFO

Keywords:
Imaging radar
GPR
Cultural heritage
Technical integration
Interdisciplinary

ABSTRACT

Imaging radar has been dramatically developed over the past decades enabling a better understanding of cultural heritage from a microwave perspective. Nonetheless, a dedicated survey and analysis of the performance of such technology in cultural heritage monitoring and management is required. In order to fill this gap, we first review the technology advance of imaging radar, including ground penetration radar, ground-based and airborne/satellite radar, in the focused cultural applications to grasp the development trend of these technologies. We then analyse the performance and limitations of imaging radar technologies based on their respective characteristics to facilitate the technology service in practical applications. Finally, we propose a flexible solution of imaging radar in cultural heritage through technical integration with pilot synergy applications in archaeological prospection and cultural heritage diagnosis and conservation.

1. Introduction

As per the UNESCO definition, Cultural Heritage (CH) encompass artifacts, monuments, a group of buildings and sites, museums that have a diversity of values including symbolic, historic, artistic, aesthetic, ethnological or anthropological, scientific and social significance. Its preservation is increasing concern by society considering the important role that CH plays in the evolution of people and their culture. Focusing on tangible heritage (movable, immovable and underwater), spanning from single building and monument to archaeological ruins, sites and architectural complexes, up to cultural landscapes, a growing number of technologies have been applied in this cutting-edge field (e.g., Burns, 1991; Pavlidis et al., 2007; Reimann et al., 2018; Inomata et al., 2020; Orengo et al., 2020) and among them, remote sensing is becoming prominent (e.g., Aminzadeh and Samani, 2006; Hesse, 2010; Lasaponara and Masini, 2012; Masini et al., 2018; Xue et al., 2020). Compared with optical imaging and Light Detection and Ranging (LiDAR) approaches, however, the performance and feasibility of imaging radar, including in particular Ground Penetrating Radar (GPR), ground-based and airborne/spaceborne Synthetic Aperture Radar (SAR), for CH have not been fully assessed yet. These are often constrained by the complexity of radar signal processing and lack of specialized expertise in image interpretation, i.e. limitations that should be overcome with specific initiatives of training and skills development, towards a yet-to-complete effective technological transfer into practice (Tapete and Cigna, 2017a).

GPR has been exploited for operational applications on CH for over three decades, with a constant growth of the scientific community and publications, as it has been highlighted by a recent overview based on bibliometric analyses (Gizzi and Leucci, 2018). By means of radar pulses GPR enables to explore the subsurface by analyzing the reflected signals of electromagnetic radiation in the microwave domain (Ultra/Very High

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https://doi.org/10.1016/j.jag.2022.102907
Received 3 December 2021; Received in revised form 1 July 2022; Accepted 1 July 2022
Available online 9 July 2022

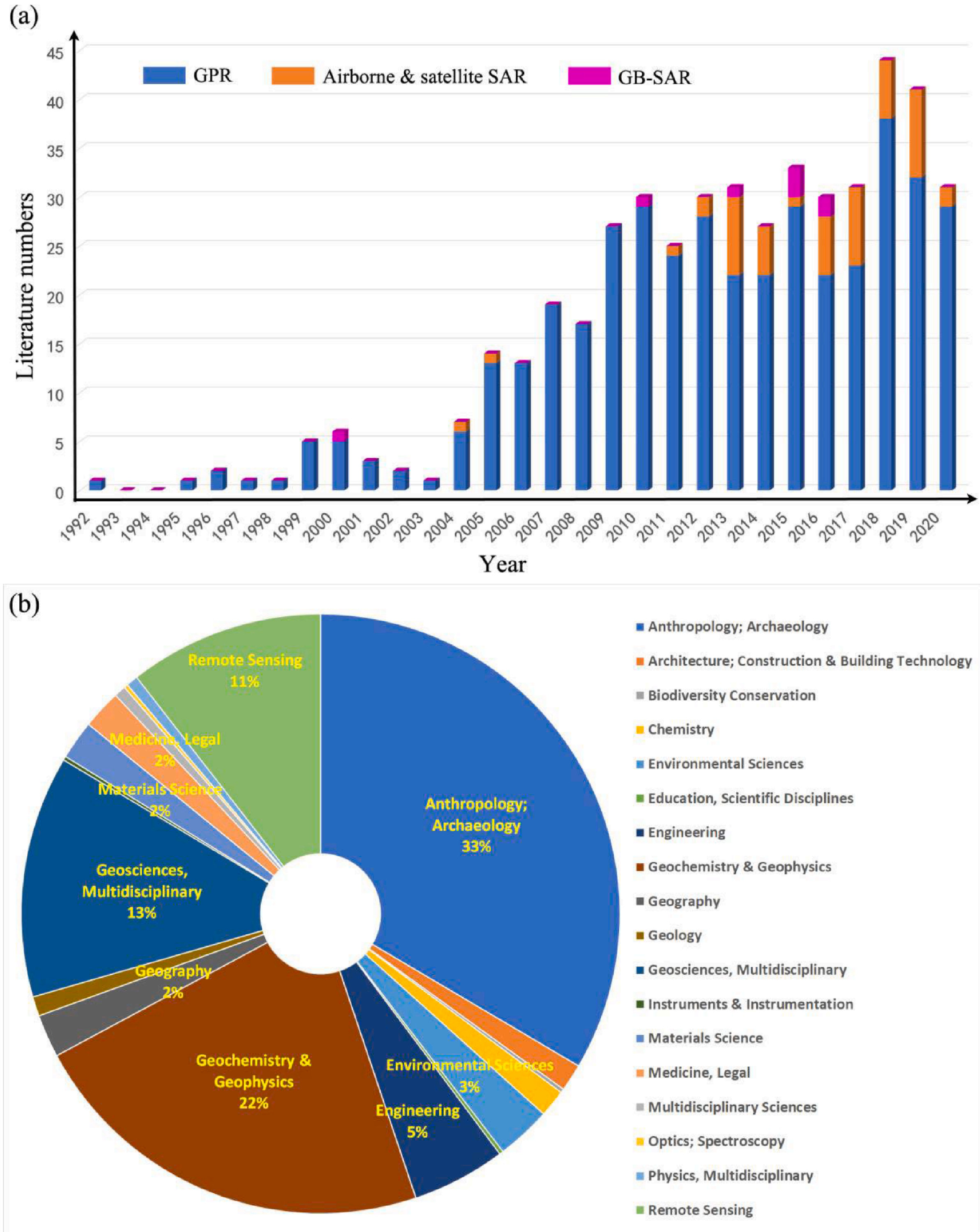

Fig. 1. Development trend of imaging radar in cultural heritage up to July 2020. (a) A solid increase of annual publications was observed in the period from 1992 to mid 2020. (b) The interdisciplinary nature of the applied basic research field indicated by the percentage of published literature in journals of different domains.

Frequency, mainly in the range 30 MHz to 3 GHz). Apart from investigation of natural media (rock, ice, soil) and engineering surveying, GPR has been progressively applied and turned into a common field instrumentation in geo-archaeological applications (Lasaponara et al., 2011) and structural health diagnosis of historical monuments (Catapano et al., 2018), owing to its capability of subsurface imaging and voids/cracks detection, and the identification of fresco detachments (Danese et al., 2018) and pattern decays of artifacts (Masini et al., 2007).

Ground-based SAR (GB-SAR) actively transmits and receives microwave signals (for example, stepped frequency continuous wave) through radar sensors. The combination of step continuous wave with Interferometric SAR (InSAR) allows the synergistic estimation of the deformation of the ancient architectural monuments and the entire cultural landscape (Tapete et al., 2013; Pratesi et al., 2015a). GB-SAR overcomes the shortcomings of spatiotemporal decorrelation of InSAR data acquired from airborne or space platforms, resulting in deformation

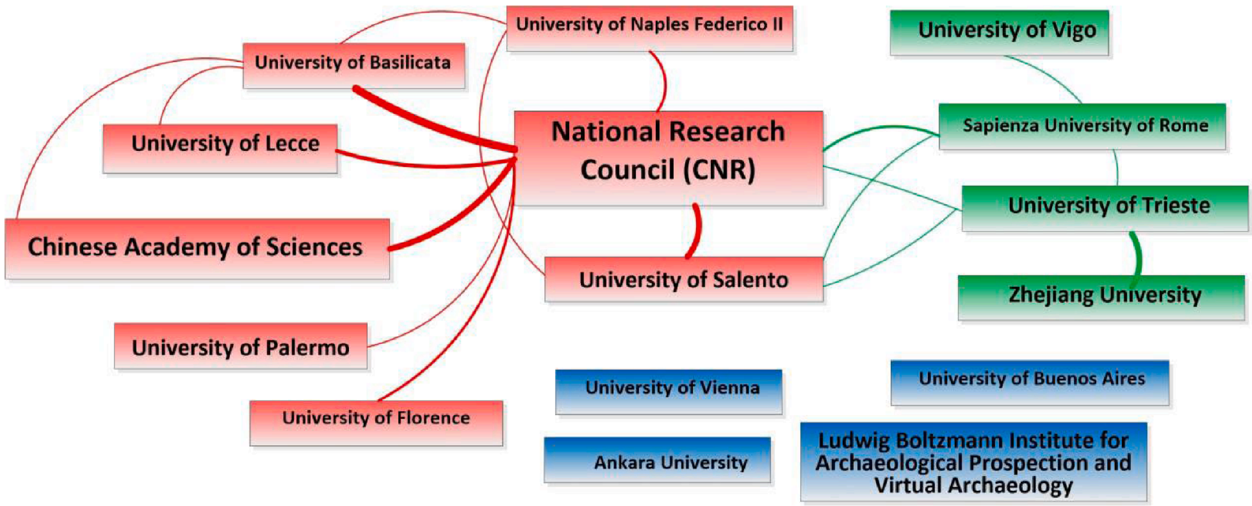

Fig. 2. Total strength of the co-authorship links with other organizations (with number of joint documents higher than 7). The thickness of lines indicates the quantity of connections.

measurements with accuracy up to sub-millimetres (Monserrat et al., 2014).

Airborne and satellite SAR technologies are increasingly attracting attention in the field of CH, owing to their capability of synoptic observation and subsurface penetration (in particular in desert landscape) using coherent and polarized microwave signatures. SAR has experienced two flourishing periods in archaeology (Chen et al., 2017b). Multi-frequency SAR investigations proved to be successful in the detection of unknown buried sites in diverse ecoregions from Mediterranean to desert areas, using proxy indicators that are linked to changes in micro-topography and soil moisture (Chen et al., 2015; 2016; Stewart et al., 2018; Elfadaly et al., 2019; 2020). In parallel, CH applications based on airborne SAR sensors, such as NASA's Uninhabited Aerial Vehicle SAR (UAVSAR) platform, have also started to be developed in the last years (Chapman et al., 2015), though they are much less common than satellite-based SAR studies. For CH monitoring, it is nearly a decade ago when the technology of Multi-Temporal InSAR (MTInSAR) was first specifically applied for early detection of structural deformation and sustainable conservation of CH sites (Tapete et al., 2012). Since then, several case studies have been implemented in different continents, with highest concentration in Europe (Tapete and Cigna, 2017b) and Asia (e.g., China and Cambodia; Chen et al., 2017a, 2017c). Furthermore, basic theoretical research has been developed with specific regard to the relationship between deformation trends of the MTInSAR time series and different styles of ground and structural deformation (Stramondo et al., 2008; Berti et al., 2013; Tomás et al., 2019).

In order to corroborate the hypothesis that imaging radar has already become an essential research tool in CH applications, at least as applied scientific research in support to investigation and conservation of CH, we implemented the approach of literature and information science to grasp the current development trend. The analysis of the existing Web of Science database allowed us not only to review the technology development, but also to identify the trajectory that imaging radar is following in oriented cultural applications which hitherto remains partly unclear, such as which types of CH are these technologies applicable to? We then systematically analysed the performance and limitations of these imaging technologies, in order to understand their adaption and methodology optimization in practical applications. This, in turn, is beneficial for the development of this specific research division by providing new insights and substantive perspectives into the future of these technologies, as well as for the practical implementation of imaging radar as a tool in the field of CH.

2. Literature review

The database of Science Citation Index Expanded (SCI-Expanded) in Web of Science (WoS, one solid citation tool) was selected for the literature review. Although earlier, broader or other types of literature may be retrieved using other bibliometric databases (e.g. SCOPUS, Dimensions, Google Scholar and etc.), the applied WoS database in this study is sufficient to obtain the development trajectory of scientific and applied research applications of imaging radar in CH. The topic search of ("synthetic aperture radar", "InSAR", "GPR" OR "GB-SAR") AND ("cultural heritage" OR "archaeo*") was applied, resulting into a total of 473 relevant publications up to July 2020. A solid increase trend of paper numbers was observed since the first publication in 1992 (Fig. 1a). The yearly number of publications in the observation period of 1992–2020 reached its peak (nearly 45 papers/year) in 2018.

The multidisciplinary character of these publications was evident for this applied basic research field (Fig. 1b), implying the necessity and importance of collaboration between scientists, engineers and site managers in order to realize the sustainable conservation of CH properties using imaging radar, and relevant data processing and information extraction technologies. These figures find a good agreement with the outcomes from similar searches (Agapiou and Lysandrou, 2015; Luo et al., 2019; Pieraccini and Miccinesi, 2019; Tapete and Cigna, 2019b).

The strength of co-authorship and bibliometric links among organizations obtained by the VOSviewer tool indicates the institutional cooperation at both national and international level (Fig. 2). The results of the analysis reveal that nowadays the National Research Council (CNR) of Italy plays a pioneering role for the use of imaging radar in CH. As the lead research institution in Italy, CNR has established a wide and close network with other institution and universities internationally, including the Chinese Academy of Sciences (CAS), who is increasingly been active in this multidisciplinary basic research and oriented applications. However, the collaborative network of CAS is still limited (i.e., concentrated on the cooperation with CNR), hence collaborations with other international research institutions could be exploited by pilot projects and/or programmes in the future.

The existing CAS-CNR collaboration highlighted the importance of using radar technologies, including SAR, in the context of multidisciplinary application projects, to facilitate the use of radar images for archaeological purposes (Chen et al., 2016; Jiang et al., 2017; Masini et al., 2017). Image interpretation represents a pressing crucial issue to be addressed. In some cases, it is the factor which limits the broader use of satellite radar technology in archaeology by non-expert users. In particular, the Italian-Chinese cooperation approach proposed in the

Table 1
Products, processing chains and consolidated applications of current imaging radar sensors (platforms) for cultural heritage. 2D and 3D indicate two-dimensional and three-dimensional, respectively.

Sensors	Products	Processing chain	Consolidated applications
GPR	Profiles/ Tomography	2D radargrams / depth-time slices for 3D tomography	Subsurface archaeology / monument diagnosis
GB-SAR	Deformation map	Interferometry (interferograms, DInSAR, MTInSAR)	Deformation monitoring & evaluation
UAVSAR	Images; DEM	Coherence / amplitude change detection; Interferometry	Landscape archaeology & change detection
Space-borne SAR	Images; Deformation map; change map; time series; DEM	Coherence / amplitude change detection; Interferometry (inteferograms, DInSAR, MTInSAR)	Landscape archaeology & change detection; Deformation monitoring & evaluation; Topographic surveying

"*Smart management of cultural heritage sites in Italy and China: Earth Observation and pilot projects*", which was borrowed from previous CNR experiences in South America (Lasaponara et al., 2016), was aimed at comparing the effectiveness of the various remote sensing technologies (active and passive), in pilot projects in Henan and Xinjiang (China). This evaluation was carried out with on-site validation, direct (excavation tests) and indirect (through geophysics), producing an advancement in both SAR data processing and interpretation approaches ad hoc devised for archaeological applications (Chen et al., 2016; Jiang et al., 2017; Masini et al., 2017).

3. Trajectory of technology development and oriented applications

The literature review indicates that imaging radar has been a prominent tool in the field of archaeology, the monitoring and assessment of monuments, artifacts and entire CH sites taking advantage of sensor's operation characteristics and relevant technology/methodology development in the aspects of image processing, information extraction and knowledge mining. CH in this review mainly refers to archaeological ruins, cultural landscapes, monuments and architectural complexes. We highlight data processing chains and relevant products of current radar sensors (platforms) to facilitate the understanding of the role of imaging radar in aforementioned CH applications (Table 1).

3.1. Technology advance and applications of GPR

GPR systems image electrical discontinuities in the medium (Masri and Rakha, 2020), by means of modulated pulses transmitted and reflected in the time domain, thus allowing the acquisition of subsurface profiles and vertical radar sections (Solla and Riveiro, 2016). The identification of the target is linked to variations in the electromagnetic properties (electrical conductivity, dielectric permittivity, and magnetic permeability).

The antenna is the most critical part of GPR devices which can be divided into two main types: ground-coupled shielded and air-coupled horn antennas. The first is the most commonly applied in archaeological applications but it can be limited on irregular surfaces due to the coupling problems that can be faced using horn antennas. In the last few decades, the enhancement of GPR systems in terms of speed and areal coverage has been obtained by the development of multi-channel configurations. Adopting a cross-profile spacing of 1/4 wavelength of the transmitted impulse into the ground between adjacent antennas, multi-channel systems enable a complete and full-resolution imaging for a site (Grasmueck et al., 2004; Trinks et al., 2018). With the high-density on the ground at a 1/4 wavelength, the interpolation of the collected adjacent profiles to generate 3D volume is not more necessary, except to fill in the gaps between adjacent tracks.

The recorded data are generally combined to form an image, named the radargram whose analysis enables the depth estimation of the individuated targets even if it is often difficult, because of the intrinsic heterogeneity of the subsurface that influences the velocity propagation of the impulse increasing the depth. The three predominant attributes, instantaneous amplitude, frequency and shape of the searched bodies, make GPR data informative for the subsurface imaging and structural evaluation. However, factors of signal attenuation, airwave events and ringing noise can adversely affect GPR waves. Consequently, to limit these issues, a pipeline for the processing of GPR data has been established by sequentially utilizing noise filters, nonlinear mapping approaches, 3D object reconstruction, and feature recognition algorithms (Tong et al., 2020).

The interpretation of high-density data can be improved using: i) time-slices, representing the horizontal variation of the amplitude (energy), for a given two-way travel time interval (depth range); ii) iso-surface of the strongest reflectors after the vertical interpolation of the calculated time-slices (Goodman and Piro, 2013) and additional models of data analysis.

The present and the near future sees the use of Unmanned Aircraft Systems (UAS) as a complementary platform for acquiring large-scale georadar data, albeit with limits in resolution and penetration capability, which can be mitigated with their integration with 'terrestrial' GPR systems (Masini et al., 2021).

GPR is widely recognized as one of the most effective geophysical surveying methods with the best available resolution within the subsurface techniques. The employment of GPR surveys in archaeological prospections ranges from studying sites that cannot be excavated, to support preventive archaeology actions and rescue survey projects: from the detection of buried structures, where high horizontal and vertical resolutions are required (Goodman and Nishimura, 1993; Pipan et al., 1999; 2001; Basile et al., 2000; Neubauer et al., 2002)) to identify archaeological landscape features (Nishimura and Goodman, 2000; Piro et al., 2003). GPR can be applied in urban areas (Masini et al., 2020), where the presence of possible sources of noise, as metallic bodies, prevent the employment of other geophysical methods, such as magnetic and earth resistance methods (Masri and Rakha, 2020).

A wide range of environmental conditions and physical parameters of the ground with respect to the electromagnetic propagation of the impulse need to be taken into account for the GPR survey planning, including high conductivity of the soil, concrete, tarmac and even fresh water; another parameter to consider is the attenuation of the signal as the depth increase. It is crucial to set an optimal compromise between depth of penetration, spatial resolution and soil conditions using interchangeable antennas at different frequencies, available in all commercial GPR systems. In the case of near-surface archaeological surveys, a common-offset antenna unit, based on separated and shielded transmitter and receiver bow-tie dipole antenna are employed. Recently GPR multi-channel systems, with two or more sets of antennas for a near-simultaneous use, have been producing (Goodman and Piro, 2013; Trinks et al., 2018). These multichannel systems offer two new opportunities: i) to rely on a range of center frequencies capable to detect targets at different depths, that is very important in case of archaeological sites characterized by more construction phases, ii) to use parallels arrays of antennas for a rapid and dense acquisition of data.

Apart from archaeological research, the GPR is the radar imaging method with the widest application in CH, being used for structural diagnosis and restoration of architectural heritage, study and conservation of artistic heritage (Fig. 3). The technological improvement of high frequency antennas (typically from 900 MHz to 2 GHz), as well as the integrated use with other imaging systems such as seismic

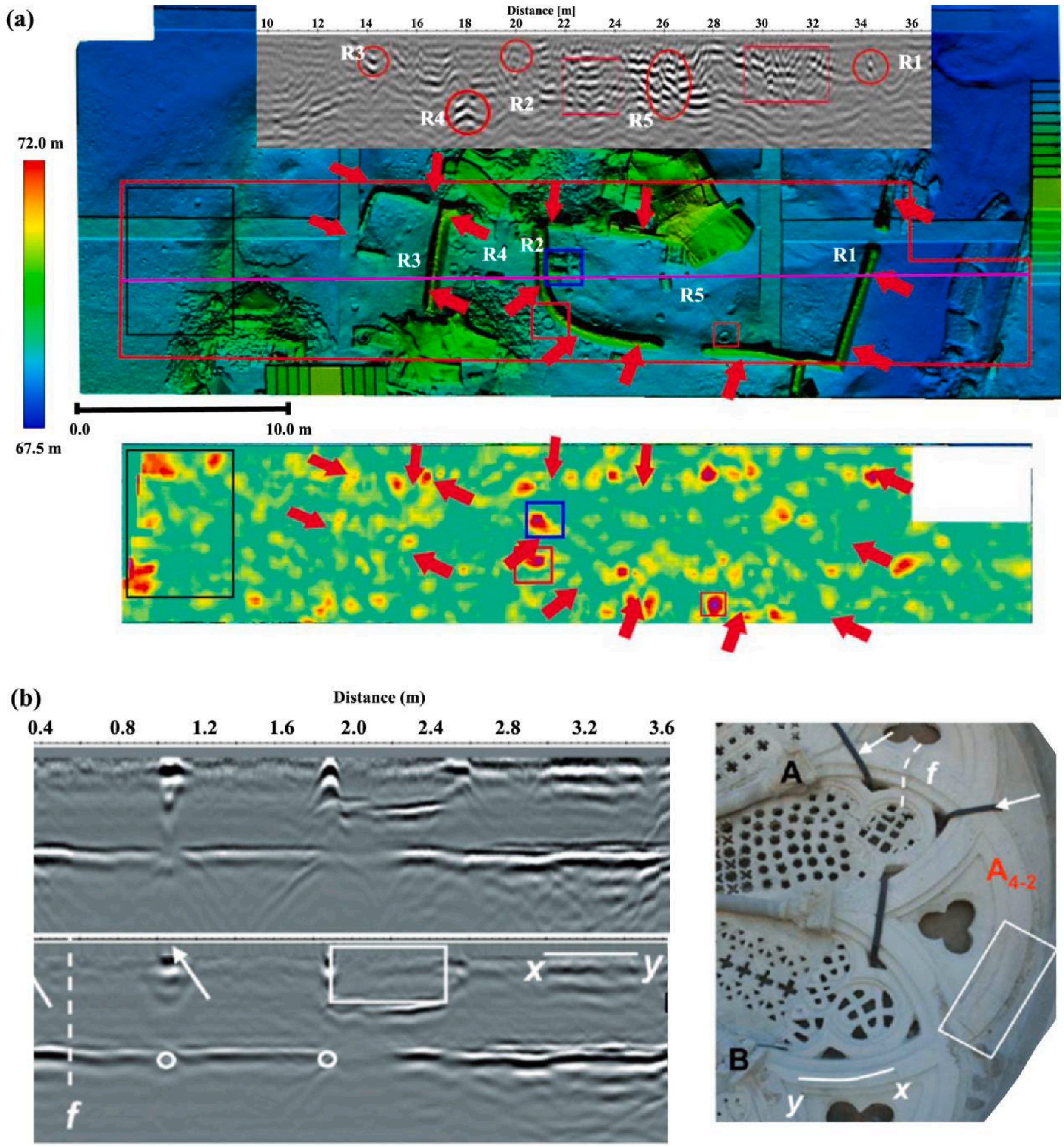

Fig. 3. GPR applications in archaeological research, and structural diagnosis and restoration of architectural heritage, referable to the archaeological site of Kaifeng in Henan (China), and the rose window of the Cathedral of Troia in Southern Italy, respectively. (a) GPR profile (upper: red circles evidence some local reflectors referable to the tops of walls of R1, R2, R3 and R5 on the DEM model acquired after the excavation) and the depth slice (lower: red arrows mark the detected of archaeological features) at 1.25 m related to GPR data (modified from Masini et al., 2017). (b) Unmigrated (upper) and migrated (lower) sections on A4-2. The white arrow denotes metallic stirrups and white small circles mark metallic tie-beams on the inner side of the rose window. The white line x–y marks a longitudinal crack and line f marks a mortar-filled fracture. The white rectangle denotes stone blocks inserted in previous restoration work (modified from Masini et al., 2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tomography, ultrasonic tests, infrared thermography have made the GPR a fundamental tool for characterizing historical masonry structures, including walls and vaults, frescoes, mosaics, and other artifacts. In this regard, it is considered essential to orient research in the development of image fusion-based approaches in order to extract from heterogeneous data for the multiple needs related to conservation. A contribution may be provided by integrating Geovisual analytics with machine learning and geospatial information. A recent application has been performed by Danese et al. (2018) who used Map Algebra, Hot Spot Analysis and artificial neural network (in particular Self-organizing Maps) to extract decay patterns of frescoes in Pompeii using high-frequency GPR data, multi-temporal infrared thermography, Red, Green and Blue (RGB) and Digital relief Models.

3.2. Technology advance and applications of GB-SAR

Differently from other terrestrial deformation monitoring techniques (e.g., point-based precise leveling), GB-SAR has gained an increasing

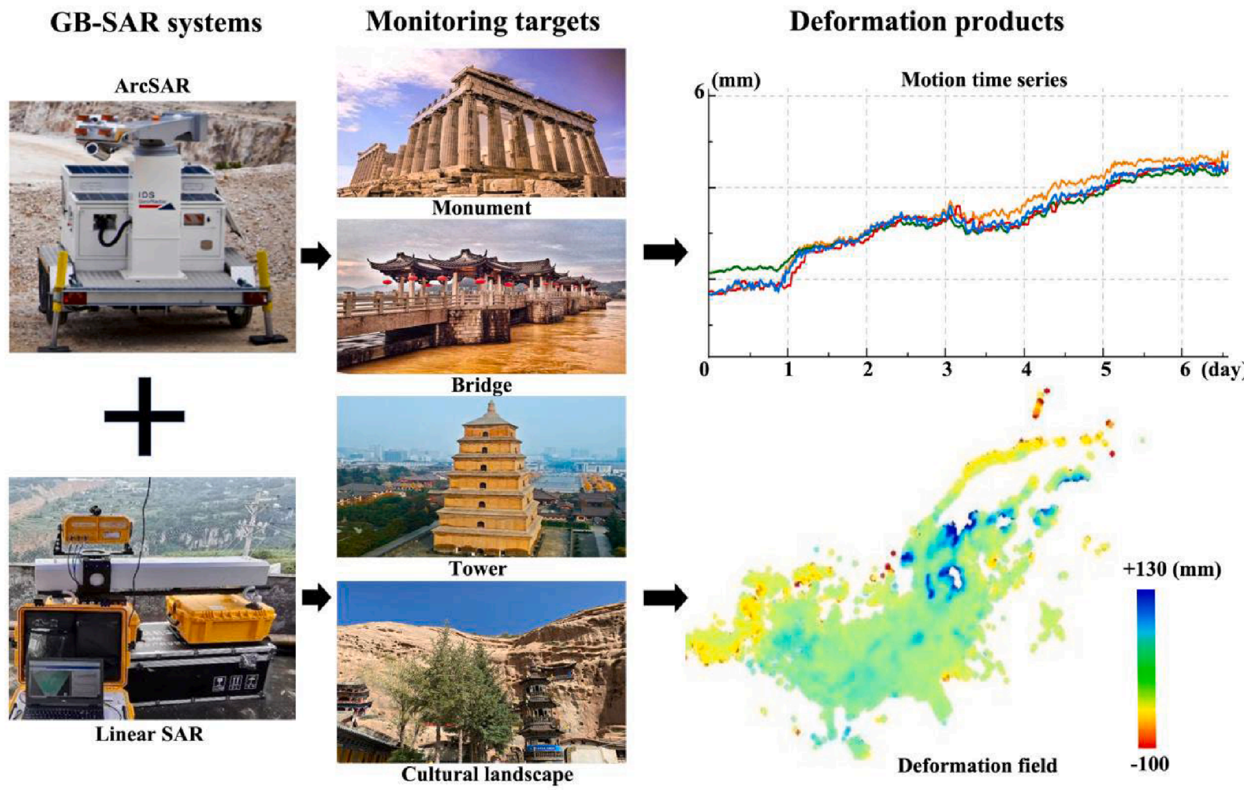

Fig. 4. Deformation monitoring of architectural heritage, such as historical monuments, bridges and towers as well as the surrounding cultural landscape using flexible GB-SAR instruments. The deformation field and motion time series on observed targets are synchronously obtained (Note that the deformation products here are schematic for illustration only).

interest in the last decade taking advantage of its high sensitivity to a wide span of deformation rates (from several mm/year to m/day), the flexible range of its measurements (from hundreds to thousands of metres) and the vast number of measurements by imaging. The capability of GB-SAR is achieved by exploiting SAR technology by moving the radar sensor along a rail track (Monserrat et al., 2014) or by applying angular scanning (Lee et al., 2013) (Fig. 4).

GB-SAR deformation monitoring can be performed either in a continuous or discontinuous mode depending on the rate of displacements that needs to be measured, or the physical environment where the sensor has to be deployed. In general, the continuous mode is a straightforward approach to monitoring moderate-fast deformations (e.g., some m/day), and the spatiotemporal decorrelation of interferograms in this mode can be negligible. Nonetheless, whenever the deformation is significant only over a relatively longer period, the discontinuous mode with repeated observations would be useful. It is to be noted that methods and models for resolving repositioning errors (Wang et al., 2019) must be elaborately utilized along with the introduction of multi-temporal InSAR approaches for tackling spatiotemporal decorrelation, in order to achieve a robust deformation estimation.

X- and Ku-band instruments are two prevailing GB-SAR systems to optimize the performance of sensor size and weight, observation maximum distance and measurement accuracy of deformations. Owing to the technology development, in the last two decades the core of GB-SAR sensors has advanced from the Step Frequency Continuous Wave (SFCW) coherent radar to the Frequency Modulation Continuous Radars (FMCW) (Iglesias et al., 2013) to improve the manageability of the instruments, as well as to reduce the acquisition times (i.e. less than 1 min). Nonetheless, the former approach is still commonly utilized in many research settings, due to the system's high flexibility.

The published literature proves that GB-SAR is mostly deployed for structural health monitoring, condition assessment, and early warning. Since the pioneering works in the 1990s (which, however, were not focused on CH), GB-SAR applications quickly developed from experimental to applied research and, in the end, commercial applications. This was thanks to an increasing offer of commercial radar interferometers from private companies, at lower cost (e.g. even the most costly Ka and W-band interferometers are less expensive given the diffusion of automotive radar (Pieraccini and Miccinesi, 2019)), and frequently provided as a full package (i.e. hardware, software, data processing and assistance) in the form of end-user-oriented services. During emergencies or in the aftermath of paroxystic events (e.g. collapses), GB-SAR serves not only to assess the condition of unstable historical monuments, ancient bridges and towers as well as the surrounding cultural landscape (Fig. 4), but it is also applied for warning purposes and public safety (Tapete et al., 2013; Pratesi et al., 2015a).

3.3. *Technology advance and applications of Airborne/satellite SAR*

Medium spatial resolution (tens of meters) and approximately one-month revisit cycle characterize the first generation of spaceborne SAR systems, from Seasat in 1978 to Advanced Land Observing Satellite (ALOS) in 2006. These revealed the potential of SAR data to sense a target at day and night with all weather conditions and, to some extent, penetrate dry sandy soils. Their exploitation in landscape archaeology was predominant in this period, in particular by utilizing the radar backscatter signal of SAR images acquired by the Shuttle Imaging Radar (SIR)-A/B and SIR-C/X missions to investigate paleo-landscapes in (sub-)tropical and arid environments (El-Baz et al., 2006). Owing to the technology development, the availability of multi-frequency, multi-polarization and high spatial resolution (up to 1 m) imagery opened a new spaceborne SAR era in the late 2000s (Chen et al., 2017b). The open and free access policy of Sentinel-1A/B data thoroughly resolved the accessibility constraint of SAR data for a wider range of applications.

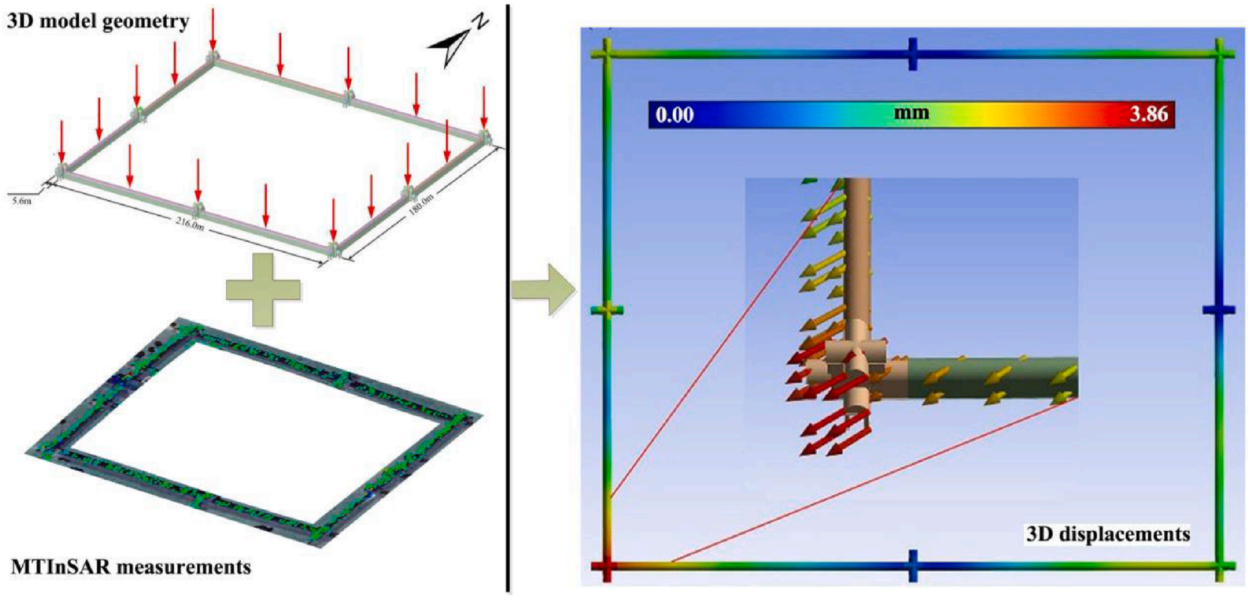

Fig. 5. Integration of MTInSAR and Finite Element (FE) simulation for the 3D displacement monitoring of the Angkor Wat Temple enclosure, Cambodia. Left-subgraph indicates the constructed 3D geometrical model (up) and derived MTInSAR deformation measurements in line of sight direction, and the right-subgraph indicates the integrated displacements from MTInSAR and FE thermal simulation (modified from Chen et al. 2021b).

However, the limited spatial resolution of Sentinel-1 Interferometric Wide (IW) swath mode (tens of meters) – which is the most used imaging mode over the landmass –, users' lack of technical skills for signal processing, and lack of familiarity with these satellite data, still hamper a stronger penetration of this technology into archaeology and CH sectors (Tapete and Cigna, 2017a). On the other side, in the field of geohazard and structural health assessment, applied geologists and engineers have increasingly exploited spaceborne SAR systems for condition monitoring in a multi-temporal dimension, and Sentinel-1 data are used, not rarely in combination with analysis of historical ERS-1/2 and ENVISAT archives (Tapete and Cigna, 2017b). Currently, new SAR missions (including commercial SAR systems recently launched by ICEYE and Capella Space) are characterized by higher spatial resolution and shorter revisit cycle of acquisitions, thus providing observation solutions that are expected to further support applications in the CH sector. An example is the new suite of Spotlight imaging modes of the COSMO-SkyMed second generation constellation, including sub-metric resolution imagery for civilian use (Tapete and Cigna, 2019a) and the possibility to collect at the same time images over two areas located hundreds of kilometres apart.

In contrast, despite their flexibility and design-orientation, the use of airborne SAR sensor platforms (i.e. NASA/JPL AIRSAR/TopSAR and UAVSAR) is still very limited in CH. Although existing collections of Polarimetric SAR (PolSAR) and repeat pass interferometry data are accessible in open access policy, the archive is geographically concentrated on mission-oriented regions (i.e., North and South America). Unless specifically collected for archaeological and CH purposes (Comer et al., 2017), the use of these data by archaeologists and heritage specialists would imply a sort of re-purposing and anyway could not necessarily allow for the same tailoring level of the observations, as in the case of new acquisitions tasked over target areas according to end-user requirements.

Applications of airborne/satellite SAR generally fall either in archaeological prospection and landscape archaeology or condition assessment. The latter divides between (i) deformation monitoring and assessment of risk due to natural hazards, and (ii) impact due to anthropogenic actions. With regard to archaeological prospection, applications are mostly scientific research, while there is no evidence that SAR has been yet included in preventive archaeology/commercial archaeology as part of infrastructural and engineering assessment projects (as it happens with aerial photography and optical satellite VHR imagery). This may be interpreted as the sign that the technological transfer process from Earth observation and remote sensing scientists to heritage practitioners and archaeologists has yet to be made. Scholars have so far focused on recognizing cropmarks, traces of buried features and remnants of paleo-landscapes, by exploiting either the subsurface imaging at given incidence angle and polarization, or the high spatial resolution, or a trade-off between these acquisition parameters (Stewart et al., 2016; Stewart 2017; Zhu et al., 2018; Elfadaly et al., 2020).

With regard to condition assessment by MTInSAR deformation analysis, the earliest applications (Zeni et al., 2011; Tapete et al., 2012) were carried out on the world-renowned archaeological site of Rome in Italy, which acted as a test bed for years for different research groups (see the overview in Cigna et al. (2014)), to move from experimental research to mature user-oriented applications of monitoring and structural health diagnosis (Della Giovampaola, 2021) and develop proper services in support of daily maintenance operations. On the other side, the Rome example stands mostly alone in the literature, and there is limited evidence suggesting that similar experiences were replicated elsewhere (although it is fair to acknowledge that some successful use cases may not be captured by a search in the scientific literature only).

In the context of an increasing level of interactions with stakeholders and local authorities, researchers are attempting multi-technique integration to interpret MTInSAR results in light of building statics (e.g., with in-situ structural health monitoring system and engineering interpretation). An example towards this direction is presented in Fig. 5 with respect to 3D displacement monitoring of the Angkor Wat Temple enclosure, in Cambodia.

User-oriented applications for the condition assessment through amplitude- and coherence-based change detection approaches have so far focused more on substantiation of natural and anthropogenic damage events in ordinary (Lefort et al., 2004; Cigna et al., 2013; Cigna and Tapete, 2013; Chapman et al., 2015; Comer et al., 2017) and crisis (Tapete and Cigna, 2019a,b) times, and on impacts due to urbanization on cultural landscapes. In this context, most of the studies are research-focused and use-case demonstrations, and this character reflects that at the moment it is hard to infer the actual user uptake of these technologies.

4. Performance exploitation and improvements

4.1. Performance and limitations of GPR

Even if the GPR method is one of the most consolidated near-surface geophysical methods employed for archaeological prospection, architectural diagnosis and preservation of artistic heritage, still there exist different aspects that could be improved to enhance the efficiency and accuracy of the applications with the aim to obtain more clear and detailed results in 2D and 3D (Goodman and Piro, 2013; Danese et al., 2018; Trinks et al., 2018).

In archaeology, the first priority needs to be taken into account is the efficiency of data acquisitions by the employment of: i) GPR antennas in simultaneous, parallel configuration, as an antenna arrays; ii) motorized vehicles which tremendously faster survey compared to manually acquisitions; iii) automatic positioning systems, as D-GPS, which accurately track the location of the GPR systems; iv) high-speed real-time sampling antenna technology which increase the measurements and data acquisition speeds. Second, the penetration depth of the GPR signature is sensitive to the dielectric constant of the surface and relevant physical properties (moisture) of the soil beneath (Goodman and Piro, 2013), and this limits the archaeological prospection of relatively deeper buried relics (Masini et al., 2017). In addition, the spatial resolution of GPR echoes decreases as the observed depth increases. This affects the reliability of this geophysical tool in archaeology, in particular considering the environmental complexity of observed landscapes. In the next future, autonomous multi-channel array systems can be used for operational applications to map large areas, in case of acquisition free of complex obstacles. GPR data sets collected with these innovative motorized multichannel systems necessarily require new data processing solutions.

In the structural diagnosis and artistic preservation, CH specialists use GPR technology to detect the internal structure of sculptures and wall paintings (Masini et al., 2007; Danese et al., 2018; Ortega-Ramírez, et al., 2021; Colombero et al., 2022) for the understanding of current issues such as the arrangement of cracks, the texture and the occurrence of voids or cavities and the modification history of those artistic assets. Generally, the diagnostic activity is informative to the restoration planning. A wooden or polystyrene plate is recommended to cover the sculptures or murals to protect them from any damage that might be caused during the GPR campaigns. Dedicated GPR surveys need to be scheduled in advance taking advantage of known information relevant to the nature, depth and dimension of expected targets, and the physical properties of the artistic material (i.e. medium permittivity and conductivity). Straight longitudinal and transverse lines are encouraged to be marked on the prepared protecting plates in accordance with the designed GPR measurements (i.e. profile interval) and to accommodate referencing of the data collected to a fixed location. The parameters of antenna frequency, trace interval, number of samples, time window, time interval are critical in GPR surveys that need to be carefully designed to assure the quality and accuracy of acquired data for the structural diagnosis of aforementioned CH assets. The 3D analysis of depth-time slices has proven to be effective for the anomaly identification using quantitative specifications (Ortega-Ramírez, et al., 2021), such as dimension and depth of excepted features. The mainly facing challenge in this field would be the accurate estimation of GPR wavelet velocities (Barraca et al., 2016) which are sensitive to the permittivity and conductivity of subsurface mediums, nevertheless they are usually unachievable precisely.

In summary, automated data processing tools are needed to check data quality, identify antenna malfunctions, to remove GPR traces based on predefined selection criteria to identify anomaly polarities. Furthermore, to improve the visualization of archaeological or structural features it will be necessary to develop ad hoc algorithms for data filtering and enhancement, as well as background removal and migration procedures.

4.2. Performance and limitations of GB-SAR

GB-SAR serves as a mean to assess either the structural stability or the dynamic behaviour of a building or construction. Focusing on the former type of application, the performance of this technology can be assessed, first of all, based on its portability. At equal conditions of non-invasiveness, the more portable is the instrumentation, the more agile is its installation in impervious locations, to overcome logistics constraints or where limited space is allowed, or no regular maintenance is possible (Tapete et al., 2013).

Associated with this, there is also the technical property of measurement distance. This is strictly linked with another key important parameter, i.e. sensibility to small displacements which, in turn, depends on the operation frequency. For example, Ku-band is sensitive to $\sim$ 0.1 mm displacements, therefore, it needs to ensure this order of magnitude for the positioning accuracy of its mechanical moving system. On the contrary, W-band is 4.5 times more sensitive, and needs a mechanical system able to guarantee 20–25 µm accuracy. Pieraccini and Miccinesi (2019) rightly recall that this is a very hard specification to guarantee for in-situ operation, and the final performance may be affected by the particular logistics conditions. Up to now, few experimental studies have been conducted to assess the capability for inspection of specific building construction typologies (e.g. wooden walls in (Sato et al., 2014)). The tailoring of GB-SAR for the preventive monitoring and health diagnosis of architectural heritage constructed by different materials (e.g. stone, masonry, metal) has not been yet fully investigated in architectural CH.

As common to all radar systems, GB-SAR devices detect motions and deformation along a predominant displacement vector, given that the observation is limited along the Line of Sight (LOS). Therefore, some assumptions prior to in-situ installation need to be made and consequent uncertainties in deformation estimation are to be accounted for (Tapete et al., 2013). A solution that may be straightforwardly thought is to use more than one device. However, in most of the cases this is not viable. Despite some tests in the past for slope monitoring (Severin et al., 2014), the use of more than one GB-SAR instrumentation operating independently is expensive and not practical (Pieraccini and Miccinesi, 2019). This consideration may be even more applicable in a sector like the CH where financial resources are typically limited, and the installation of a GB-SAR device in an archaeological area or to monitor a given monument is more likely to happen in the framework of a specific ad-hoc funded project, rather than as part of a long-term baseline monitoring activity.

One of the common outputs is a 2-D map of detected displacements which, however, could be not easy to interpret for the non-expert eye. Tapete et al. (2013) has demonstrated that geometric integration with 3D model of the monitored building can allow a more intuitive, and in turn a more correct, interpretation of the detected deformation in relation to the building statics. Therefore, a GB-SAR technology including software (and/or a web interface in case of operational services) easing such data post-processing and visualisation is definitely more effective to engage end-users and increase their uptake of the technology.

When GB-SAR is used for early warning, a key parameter is the timeliness with which the data are captured, processed and finally transformed into information valuable for end-users. Workflows engaging the end-users since the initial phases (e.g., the setup of warning thresholds) have been proved crucial (Tapete et al., 2013; Pratesi et al., 2015a) to avoid top-down approaches that, in the end, may hamper the technological transfer and user uptake.

4.3. Performance and limitations of airborne and satellite SAR

Depending on the scope for which a satellite SAR is employed – i.e. prospection of buried features or condition assessment of exposed structures and monuments –, its performance can be assessed using different proxies, metrics and parameters.

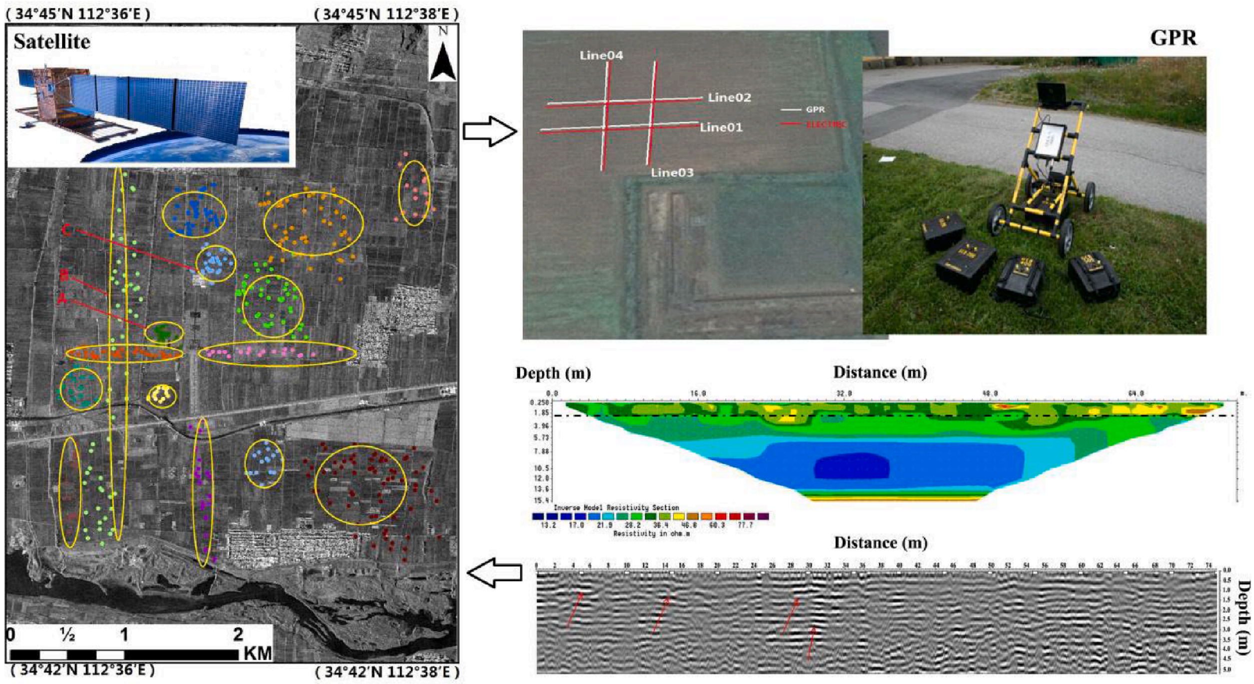

Fig. 6. Integration of GPR and SAR observations in the archaeological prospection of Han-Wei Capital City, Luoyang (China) (modified from Jiang et al., (2017)). The hotspots with archaeological interest (marked by ellipses) in the left subgraph were identified by SAR images, which in turn guided the detailed geophysical prospection of GPR (marked by Line 01–04) and electrical resistance tomography presented in the right subgraph.

With regard to archaeological prospection, the success in the use of satellite SAR imagery should be primarily evaluated based on the visibility and discernibility of the buried features. This is particularly crucial from an end-user's perspective (Balz et al., 2016). Comparison between (coeval) SAR and optical satellite imagery at very high spatial resolution is quite common in the literature to prove the match between what is visible in either one or both the images. However, the possible drawback of this approach is that, because optical imagery is always more intuitive to interpret than SAR, non-SAR readers (either archaeologists or heritage specialists) would always tend to perceive SAR imagery as less useful and less performing than optical. As a consequence, they would be less stimulated to search for and deploy SAR data for their own applications. For discovery of buried features, while it is yet to fully ascertain the actual capabilities of SAR to penetrate different media, recent research has demonstrated that a mean to assess the accuracy of feature detection is via integration with other remote sensing data (Rutishauser et al., 2017) and verification with in-situ data collected at known environmental and soil conditions (Wiig et al., 2018).

With regard to condition assessment, the abundant literature in the field of geohazards has demonstrated that the pre-requisite for satellite MTInSAR to be useful is that sufficient MTInSAR point coverage is achieved through the SAR image processing. Pratesi et al. (2015b) – and the literature (Garcia et al., 2021) following their methodology – have deployed a simple quantitative approach to use the density of points falling onto each monitored building or monument, to provide a reliable assessment of structural stability based on MTInSAR. Undoubtedly, the second fundamental aspect would be the accuracy and precision of the deformation estimates. In this respect, while the specialist InSAR literature has investigated and defined how to calculate these parameters with regard to specific InSAR processing techniques and different SAR data (e.g. Small Baseline Subset – SBAS processing of C-band data stacks in Cigna and Sowter, 2017), this practice is not yet fully adopted in InSAR applications on CH.

Studies, instead, have been conducted to assess the accuracy of MTInSAR point location on buildings (Tapete et al., 2015; Chen et al., 2017c), to make sure that the observed deformation is correctly attributed to individual architectural components of the monitored structures. Tapete et al. (2015) have demonstrated that this localization information is directly linked with the specific geometric configuration that allows the radar backscattering mechanisms, and therefore it is a means to verify the visibility of the monitored structure to the satellite LOS. The existing literature suggests that now could be the right time to move forward to pilot studies, aiming to undertake an analysis that goes beyond the mere observation of velocity values and deformation trends of the MTInSAR points found over architectures and buildings, and provides a robust correlation with the structure static.

Once the observed deformation is correctly localized, if MTInSAR is applied for purposes of early warning, another metric that can be used to assess the performance is how much in advance, and without any doubt, the displacement time series exhibit motion precursors that can warn about possible collapses (Cigna et al., 2012; Tapete et al., 2012). Instead, if MTInSAR is applied to observe slow-moving processes after building construction (i.e. settlement) or caused by anthropogenic activities on the geological subsurface (e.g. land subsidence due to groundwater exploitation), the metric to use is how the displacement time series best fit the expected deformation based on structural and engineering geology consolidation models (Stramondo et al., 2008; Pratesi et al., 2016).

The above applications are feasible and can lead to fruitful outcomes if sufficient archive SAR images are available in the catalogues and have been collected either on a regular basis or with a constant short revisit time. The denser and more frequent are the observations composing a single deformation time series, the better representation of the multi-temporal deformation can be provided by MTInSAR, the less likely is that the assessment is dependent by ephemeral trend changes or unable to sense shorter scale non-linearities. For example, unprecedentedly long Sentinel-1 data stacks were beneficial to constrain the multi-temporal evolution of land subsidence affecting the territory where the archaeological site of Capo Colonna in southern Italy is located (Cigna and Tapete, 2021). High frequency and regularity of the SAR observations are equally advantageous conditions to undertake quantitative condition assessment in case of intentional destruction of archaeological heritage, such as looting (Tapete et al., 2016). Lack of

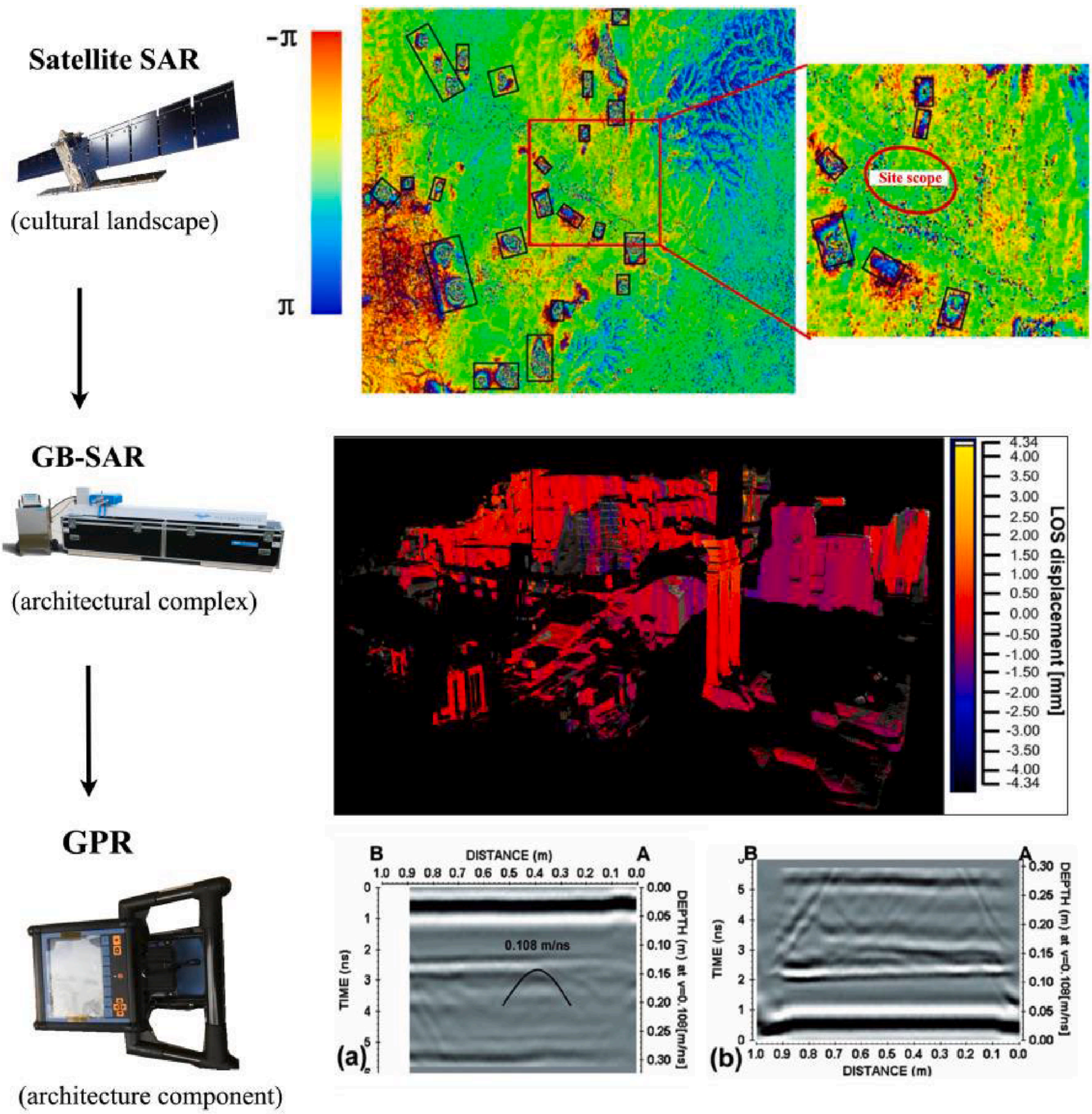

Fig. 7. Conceptual integration of GPR, GB-SAR (modified from Tapete et al., 2013) and satellite SAR observations in the CH condition monitoring and assessment. Surface displacements calculated using the satellite InSAR technology provide hotspots of the architectural complex for structural instability monitoring using GB-SAR, which in turn guides the hazard diagnosis of concerned monument components.

data and interruptions in the image time series covering a specific heritage site may affect the accuracy with which hypotheses about when a specific observed damage has occurred are made. At the same time, images that are collected on a regular basis (e.g., as part of a background mission schedule) are essential to capture, even retrospectively, events of damage to heritage that are very difficult to anticipate (Cigna and Tapete, 2018).

5. Discussion

As described above, the performance (i.e. spatiotemporal resolution and operation characteristics) of imaging radar of GPR, GB-SAR and airborne/satellite SAR in CH varies from each other, although they are exploiting the same type of electromagnetic wave for imaging. Having high acquisition efficiency, the discernibility of archaeological features from airborne/satellite SAR images however tends to be challenging due to the intrinsic weak archaeological signatures disturbed by the speckle noise. Consequently, the reliability of SAR remote sensing in archaeology needs to be further validated by geophysical investigations, such as GPR in which the regions of interest for prospecting need to be provided in advance. In a similar manner, airborne/satellite SAR is optimized for a cost-effective and less time-consuming condition monitoring of the entire cultural landscape. However, a trade-off is required when the extracted signature is sensitive to the geometry of imaging and/or the spatiotemporal resolution of SAR data cannot be assured. These limitations in turn can be mitigated using the customized GB-SAR and GPR observations, although the a priori knowledge of faced problems or the deterioration of cultural assets needs to be at least preliminarily known.

In order to pinpoint their respective advantages, technology integration can be an optimized solution (Davis et al., 2021). Spaceborne SAR in archaeology can be fully exploited in arid-remote regions owing to its capability in wide-scale imaging, sub-surface penetration and feature identification, once it is verified that the multispectral resolution of optical remote sensing is intrinsically limited. Automated algorithms and approaches (Stewart et al., 2020; Orengo et al., 2020; Davis et al., 2021) oriented to archaeological trace detection need to be introduced and/or developed, such as machine-learning classification, to enhance the robustness and efficiency of data processing in particular in the era of Big data nowadays. After that, more in-depth investigations can be carried out in archaeological sites, or even specific subzones with the archaeological interest or past human-being traces, using high-resolution products derived from SAR data (i.e. DEM) and GPR prospection. It is to be noted that, the performance of GPR in dry-arid environments can be maximized considering the suppressed soil moisture and consequently the enhanced penetration of radar signatures. To prove the feasibility and effectiveness of technological integration in archaeology, we conducted a pilot case study in Han-Wei Capital City, Luoyang, China (Fig. 6). We detected regions of archaeological interest (highlighted by ellipses) using a decision-tree classifier for X-band COSMO-SkyMed SAR images (3 m resolution). These hotspots, presenting temporal archaeological vegetation marks, were further validated by the geophysical prospection, in particular the GPR profiles.

In CH monitoring, GPR, GB-SAR and airborne/satellite SAR images are generally complementary considering their operation characteristics and the phenomena that they can depict. Owing to the development of spaceborne SAR interferometry, the motion anomalies at the cultural-landscape scale can be quantitatively measured with precision up to millimeters, providing precursors for the structural instability monitoring of single monument with significant heritage values using GB-SAR and its 2D motion measurements. Structural issues affecting monuments can be further identified using the healthy diagnosis model of portable GPR by providing the occurrence of structural fissures or cavities. The conceptual synergy application of GPR, GB-SAR and satellite SAR in the preventive monitoring of architectural heritage (Fig. 7) indicates the potential of the technical integration to foster a cost-effective and efficient hazard surveillance taking advantage of their synoptic-dedicated observation views and quantitative static-dynamic measurements. In other words, the geolocation and amplitude of surface displacements (i.e. caused by mining or groundwater pumping) surrounding the entire cultural landscape was obtained using satellite InSAR technologies. It provided vulnerable regions of interest where the architectural complex overlaid needs to be intensively monitored, such as using the GB-SAR. The structural issues of CH assets could be further confirmed by analyzing the GPR data that is a consolidated technique for the detection of underground voids, cavities and fissures for the observed architectural component.

6. Summary and perspectives

A comprehensive, dedicated review and performance analysis of the microwave imaging radar, including GPR, GB-SAR and airborne/satellite SAR, in CH studies and applications is provided with the aim to address the current knowledge gap between what science has achieved in this field of remote sensing and what end-users could benefit from if these technologies were integrated and implemented in real-world case studies. Past investigations reveal the necessity of technological combination and interdisciplinary investigation (Chen et al., 2021a), in particular hitherto their synergies in CH applications are still rare and need to be further exploited.

Based on this evidence, a viable solution to facilitate the booming development of this cutting-edge direction is to combine all these technologies. GPR, GB-SAR and airborne/satellite SAR are intrinsically complementary based on their observation views (subsurface-ground-space eye) and for monitoring scopes (visible and invisible condition alteration), resulting into the optimized performance through technological integration, which has further been confirmed by the pilot synergy applications as shown in Figs. 6 and 7.

At the same time, we highlight the significance of the *trans*-boundary collaboration in CH studies in coordination with professionals (scientists, engineers, managers, stakeholders and etc.) with diverse expertise (anthropology, architecture, engineering and etc.) considering the interdisciplinary nature of CH studies. We also recommend the inclusion of frontier information technologies (i.e., artificial intelligence, Big data, cloud computing, spatial information and Internet of Things) to make the best out of the enormous amount of data that radar technologies can provide, and generate information ready for further value-adding via sharing and direct engagement of CH end-users and stakeholders.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

We acknowledge the jointly funding from the Strategic Priority Research Program of the Chinese Academy of Sciences [Grant No. XDA19030502], the Jiangxi Provincial Technology Innovation Guidance Program (National Science and Technology Award Reserve Project Cultivation Program)[Grant No. 20212AEI91006] and the National Key Research and Development Program of China [Grant No. 2017YFE0134400].

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