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An overview of satellite synthetic aperture radar remote sensing in archaeology: From site detection to monitoring

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ABSTRACT

In the last two decades, archaeology has benefited from the development of earth observation (EO) technologies, including optical multispectral, LiDAR and synthetic aperture radar (SAR) remote sensing. The latter is gaining the attention of an expanding community of scientists and archaeologists due to the increasing availability of multi-platform, multi-band, multi-polarization and very high-resolution satellite SAR data. It is increasingly becoming an important tool in archaeology owing to specific characteristic of its operational modalities, e.g. all-weather, penetration, polarization and interferometry. However, compared to other EO technologies, SAR is encountering more difficulties in realizing its full potential for archaeological applications due to the greater complexity of data processing and interpretation tools. In this paper, SAR-based approaches for the reconnaissance of archaeological signs and SAR interferometry for the monitoring of cultural heritage sites are discussed. Ways and means to reduce complexity of data processing and interpretation tools are also explored.

1. Research aims

The paper deals with the state-of-the-art spaceborne SAR remote sensing for archaeology, including SAR-based approaches for the reconnaissance of archaeological signs and SAR interferometry for the monitoring of cultural heritage sites. It also discusses the optimization of SAR data for typical problems of archaeological researches.

2. Introduction

The availability of numerous multifrequency, multi-polarization and very high-resolution (VHR) satellite SAR data has opened a new era in the spaceborne radar technology. This is particularly important for a number of applications, as in archaeology, that was historically limited by low spatial resolution of the early satellite SAR sensors. Up to now, research based on spaceborne SAR data have been generally limited compared to that based on optical imagery, due to the scarce public availability of data, complexity of data processing and software and the difficulty of interpreting the results from an archaeological perspective. Today, satellite SAR has entered into a golden era of applications mainly due to the increasing availability of abundant historical archives and active satellite platforms, ranging from free of cost, as provided via Sentinel-1, to high-resolution data available through TerraSAR/TanDEM-X, COSMO-SkyMed, Radarsat-2 and ALOS PALSAR-2. The latter offers data at a scale of one meter or higher. Furthermore, a number of user-friendly commercial and open source software have been recently developed. We now have around twenty spaceborne SAR sensors operating (Table 1) and new SAR systems will be launched within the next 5 years assuring a rich availability of data for the coming years.

The use of multifrequency, multisensor, multitemporal, quad-polarization (as PALSAR-2) SAR data can provide powerful information for archaeological investigations [1] ranging from archaeological/historical landscape, former environment, site detection (buried or emerging archaeological remains) and monitoring. SAR can overcome limits of passive optical data in being able to sense a target at any time of day or night, and, to some extent,

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Table 1
SAR system parameters.

SAR system	Band	Polarization	Incident angle (°)	Resolution (m)	Swath width (km)	Organization	Altitude (km)	Orbit inclination (°)	Launch year
SEASAT	L	HH	23	25	100	NASA	790	108	1978
SIR-A	L	HH	45	30	50	NASA	225	57	1981
SIR-B	L	HH	20–60	30	50	NASA	225	57	1984
ALMAZ-1	S	HH	30–60	15	20–45	RSA (PKA)	300	72.7	1991
ERS-1	C	VV	24	25	100	ESA	790	97.7	1991
JERS-1	L	HH	35	18	76	NASDA/MITI	568	97.7	1992
SIR-C	C, L	All	17–60	25	15–100	NASA	225	57	1994
X-SAR	X	VV	17–60	25	15–40	DLR/ASI	228	57	1994
ERS-2	C	HH	24	25	100	ESA	785	97.7	1995
SAR-SAT	C	HH	17–50	10–100	50–170	CSA	790	98.6	1995
PRIRODA	S, L	HH	35	30	120	RSA/DLR	394	51.6	1995
Radarsat-1	C	HH	10–59	10–100	50–500	CSA	796	98.6	1995
ENVISAT	C	All	20–45	30	50–400	ESA	800	100	1998
SRTM	C	HH	20–60	30	60	NIMA/NASA	233	57	2000
PALSAR	L	HH; VV; HV; VH	20–55	10–100	70–250	NASDA/MITI	700	98	2002
Light SAR	L	All	20	25–100	50–500	NASA	790	97.7	2003
Radarsat-2	C	All	20–60	3–100	20–500	CSA	796	98.6	2007
COSMO-Sky Med Scan SAR	X	One and two polarization modes (HH, VV, HV, or VH)	20–59	16–100	100–200	ASI	620	97.8	2007
COSMO-Sky Med Strip Map	X		20–59	3–20	30–40	ASI	620	97.8	2007
COSMO-SkyMed Spot Light-2	X		20–59	1	10	ASI	620	97,8	2007
TerraSAR-X Spot Light mode	X	(HH, VV), (HH/VV)	20–60	1	10	DLR-ASTIRUM	514	97.44	2007
TerraSAR-X Strip Map mode	X	(HH/VV), (HH/HV), VV/VH	20–60	3	30	DLR-ASTIRUM	514	97.44	2007
TerraSAR-X Scan SAR mode	X	HH, VV	20–60	18.5	100	DLR-ASTIRUM	514	97.44	2007
TerraSAR-X Staring Spot Light mode	X	HH, VV	20–60	Up to 0.25	4–5	DLR-ASTIRUM	514	97.44	2013
Sentinel-1 Strip Map	C	VV + VH HH + HV	20–45	5	80	ESA	693	98.18	2014
Sentinel-1 Interferometric Wide		HH VV		5 × 20	250				
Sentinel-1 Extra Wide				20 × 40	400				
Sentinel-1 Wave mode				5	20				
PALSAR-2 Spot Light	L	HH, VV, HV	8–70	1–3	25	JAXA	636–639	97.92	2014
PALSAR-2 Strip Map		HH, VV, HV (HH + HV), (VV + VH) (HH + HV + VV + VH)		3/6/9	50–70				
PALSAR-2 Scan SAR		HH, VV, HV (HH + HV), (VV + VH)		100	350–490				

National Aeronautics and Space Administration (NASA); Shuttle Imaging Radar-A (SIR-A); Shuttle Imaging Radar-B (SIR-B); Russian Space Agency (RSA); European Remote-Sensing Satellite-1 (ERS-1); European Space Agency (ESA); Japanese Earth Remote-sensing Satellite-1(JERS-1); National Space Development Agency (NASDA); Ministry of International Trade and Industry(MITI); Shuttle Imaging Radar-C (SIR-C); X-Band Synthetic Aperture Radar (X-SAR); Deutsche Forschungsanstalt fur Luft-und Raumfahrt (DLR); Agenzia Spaziale Italiana(ASI); European Remote-Sensing Satellite-2 (ERS-2); Search And Rescue Satellite Aided Tracking (SAR-SAT); Canadian Space Agency (CSA); Synthetic Aperture Radar Satellite-1 (Radarsat-1); Environmental Satellite (ENVISAT); Shuttle Radar Topography Mission (SRTM); National Imagery and Mapping Agency (NIMA); Phased Array type L-band Synthetic Aperture Radar (PALSAR); Synthetic Aperture Radar Satellite-2 (Radarsat-2); Phased Array type L-band Synthetic Aperture Radar-2 (PALSAR-2); Japan Aerospace Exploration Agency (JAXA).

'penetrate' vegetation and soil depending on sensor bands, surface characteristics (ice, desert sand, close canopy, etc) and conditions (surface moisture content).

Different from optical, SAR remote sensing actively transmits signals and then receives backscattering of observed scenarios for imaging. Generally, there are two components in a SAR image [2,3]:

- the backscattering amplitude;
- the phase.

The first is influenced by speckle, layover, shadow and foreshortening, and the second by the variation of backscattering and movements. Exploiting the backscattering in terms of intensity or polarization [4] we can retrieve information on the surface characteristics (revealing in some cases the presence of archaeological features); whereas exploiting the phase information, we can obtain topography and subtle deformations from interferometric analyses based on multiple data acquisitions, such as tandem configuration or a multitemporal dataset. Topography is an important factor influencing the detection and discovery of heritage targets (e.g. proximity to ancient rivers or located in high-level wetland platforms) [5], whereas, the identification of subtle deformations has potential relevance for preventive diagnosis of the vulnerability of monuments and surrounding environments and providing early-warning risks [6].

Satellite SAR is a rapidly evolving remote sensing technology that offers great potential for detecting, documenting and monitoring heritage targets in tropical regions (cloud penetration capability), in dry-sand sediments (soil penetration capability) as well as in Mediterranean climates (capability of anomaly detection, in terms of moisture, vegetation and corresponding archaeological features). This paper provides a short review on the main stages of evolution and the progress in satellite SAR remote sensing techniques and their application in archaeology.

3. Radar space view of archaeological features

3.1. Physical basis

SAR signal has various properties that can be exploited for archaeological prospection. The backscattering coefficient informs us about surface characteristics according to the wavelength range (band), incidence angle, and polarization. It is important to consider that there are significant differences between the interpretation of microwave and optical images. A correct interpretation of radar images is not a straightforward task and requires knowledge about ground surface conditions as well as about the interaction mechanisms between radar waves and surface sensed. First of all, it should be considered that for each pixel, the intensity represents the proportion of microwave backscattered from the target area, whose value depends on a number of factors or parameters including the characteristics of the radar system (frequency, polarization, viewing geometry, etc.) as well as on the characteristics of the surface (landcover type, topography, relief, dielectric constant, moisture content, conductivity, etc) and features (i.e. surface roughness, geometric structure, orientation). Many of these characteristics and parameters are closely interrelated so that the brightness of features in an image is usually a combination of several variables. Nevertheless, the parameters that have a key role in the interactions between radar energy and target are:

- surface roughness;
- radar viewing and surface geometry relationship;
- moisture content and electrical properties of the target.

3.2. Space radar for archaeological prospection

Human activities over time produce landscape alterations and environmental changes that can be recognized even after centuries and millennia. The traces of such alterations are generally subtle. Furthermore, the deposition processes and/or alluvial phenomena tend to mask these signs.

Other kind of signs related to human frequentation is linked to the presence of organic materials or ash introduced by prehistoric occupants. They can be detected based on changes in soil composition, superficial roughness and/or moisture content as revealed by radar satellite sensors. The reconnaissance of archaeological signs by radar data is more complex than that feasible using optical data [7–10] due to a greater number of factors characterizing the SAR geometry acquisition and interaction mechanisms towards radar-targets. For an easier understanding of the problem, we refer to the classification of archaeological signs (shadow/crop/damp) [11] commonly used in the optical remote sensing domain [8].

In optical images acquired with low angle sunlight conditions the shadow can reveal the presence of cultural micro/medium-topographic relief related to earthworks, platforms, ditches and shallow remains. On the other hand, in radar data, only very steep slopes cause shadows, which rarely provide any information of cultural interest. However, the detection of cultural topographic relief is possible, though it is strongly conditioned by the acquisition geometry and incidence angle which should be given due consideration. A model simulating the interaction between radar energy and the most common topographic relief of cultural interest is lacking. On the base of some experiences of the authors in some sites in Peru and Northern Africa and by approaching the problem in an heuristic way, the interaction between radar and micro/medium-topographic relief could be seen according two different response modes (Fig. 1):

- diffuse backscattering for microrelief (that is rough surface);
- and double bounce, when the radar detect outstanding relief.

In the latter case, the pixel brightness is greater relative to the first one, thus facilitating the extraction of cultural features. In the first case, geometric shapes could facilitate the interpretation of surface roughness (linked to microrelief) as potential archaeological patterns.

The observation of crop-signs is the most effective way to identify features of archaeological interest by using and processing optical data with any spectral resolutions in the visible and near-infrared domain [8,10,12–14]. The presence of buried walls and/or filled ditches produce local variations in moisture and nutrients content and, consequently, in the growth of vegetation, which are all detectable by observing and analyzing the spectral response. On the other hand, it is much more complicated to understand and model the interaction between radar and surface in the case of crop-signs. We are in presence of a great number of factors and interaction mechanisms whose effects are far from being discriminated. A promising approach is based on multitemporal amplitude data processing particularly when SAR image acquisition covers an entire plant growth cycle [11,15]. However, also single data analyses along with the use of adequate filtering methods could provide good results. In this case, it is important to select data acquired in the most favorable period of crop-signs when they are associated with the greatest spatial change in moisture content [11].

Damp marks occur when archaeological deposits, such as buried walls, filled ditches and pit etc., induce local changes in the drainage capability of the soil. This could reveal moisture changes whose visibility from optical remote sensing data [8] depend on the soil type, climate and meteorological conditions, and, the nature of remains.

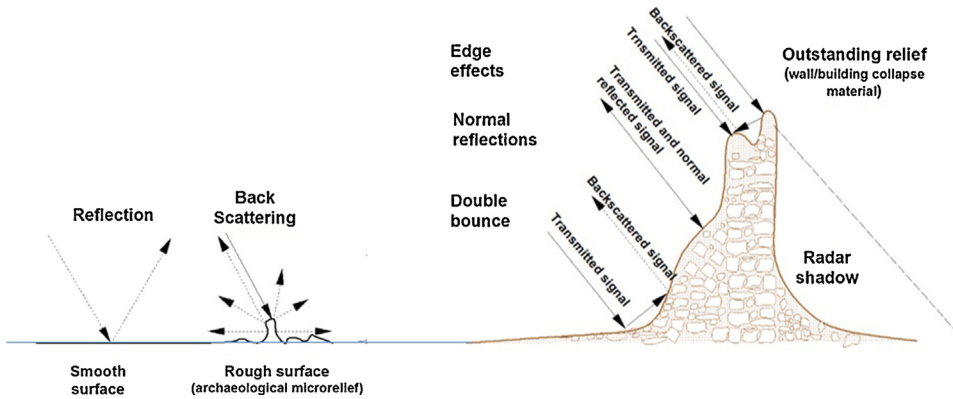

Fig. 1. Heuristic model of interaction between radar and some typical archaeological features.

The same moisture induces variations in the dielectric property of the soil and consequently the scattering of radar signal.

Compared with optical imagery, penetration is one of the principal merits of SAR remote sensing. This capability is useful for detection of relics in rainforests and buried remains (settlements and ancient water systems) in deserts using backscattering. Penetration depends on the wavelength (the longer wavelength the deep penetration), as well as on surface properties (roughness and moisture content) and imaging geometry. Until today the lack of high-resolution data at bands with greater penetration capability (i.e. L- and P-band) limited the use of SAR data for detecting buried remains. The recent launch of ALOS-2 carrying onboard PALSAR-2 capable of acquiring data at higher resolution (1×3 m per pixel in Spotlight mode) could open encouraging perspectives in the field of archaeological prospection.

As a general role, the ability to discriminate archaeological signs is an issue linked both to the ratio signal-noise and to the differential scattering behavior between target/feature and its surrounding. Some recent applications suggest a strategy based on the use of filtering, the multitemporal data processing when the data are available, and the knowledge of the problem/site to investigate in order to perform a careful choice of the data acquisition period especially for the detection of seasonal variations [11]. Moreover, it should be considered that the acquisition geometry and the SAR illumination according to the ascending or descending acquisition could affect the visibility of archaeological signs and heritage targets. As an example, Fig. 2 shows some linear archaeological features of Great Wall near the Yumen Frontier Pass. Such features are more evident in ascending acquisition than in descending acquisition due to its parallel direction compared with the satellite flight path.

3.3. Progress of spaceborne SAR technologies in archaeology

Unexpected capabilities for archaeology were accessed by NASA researchers from data provided by the first shuttle imaging SIR-A: unknown palaeochannels buried under the desert in northern Sudan and southern Egypt were identified by McCauley et al. [16]. This discovery lead to subsequent implications in the geoarchaeology of prehistoric environments of the region (see also [17]). An old buried river system was detected later using SIR-A data in the Taklamakan desert [18]. Guo [19] identified the ancient

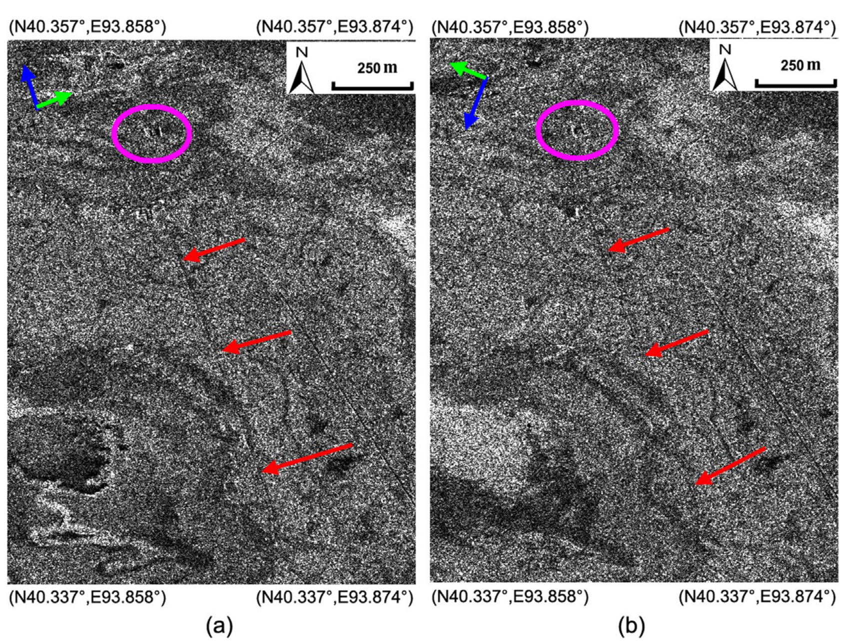

Fig. 2. Two TerraSAR-X Stripmaps images (a) and (b) related to the same scene including the Great Wall in Han dynasty (marked by red arrows) and Yumen Frontier Pass (marked by the purple ellipse), and acquired in ascending and descending mode, respectively. Blue and green arrows indicate the flight path and direction of SAR illumination. The two data have been acquired on 28.04.2013 with 41° incidence angle and 23.09.2012 with 39° incidence angle, respectively.

Great Wall in Sui and Ming dynasties in the border area of the Ningxia Hui Autonomous Region and Shaanxi Province, China using multi-band and multi-polarization SIR-C/X-SAR data. Blom et al. [20,21] discovered the lost City of Ubar in the desert of Oman (http://visibleearth.nasa.gov/view_rec.php?id¼536). To overcome the drawbacks due to low spatial resolution, they identified the urban settlements by investigating the convergence of several ancient roads. Finally, Maya's ancient irrigation canals and cultivated wetlands were discovered in the Yucatan peninsula using SEASAT data [22–26]. Generally, the occurrence of human settlements is in proximity to water-sources; Richason III and Hritz [27] investigated settlements and river systems using the Canadian SARSAT data in the lower Mesopotamian Plain (Nippur archaeological sites in Iraq); other discoveries were made in the monumental site of Angkor, Cambodia using NASA SAR data [28,29].

Nevertheless, during the last decade, the application of imaging SAR in archaeology has been limited due to the relatively low spatial resolution of SARs (in L- and P-bands), the complexity in interpreting data from SAR-based products, and the difficulty to access low-cost data sets (such as SIR-A, SIR-B, and SIR-C). The huge archives, currently available with their friendly user-access (see ESA and NASA catalogues), has recently stimulated new interests in the use of spaceborne SARs in archaeology, thus giving fresh impetus to this research field (see the special 2013 issue of *Archeological Prospection* [30–33]). SAR derived products have been also used in the context of a holistic research including archaeological record, to provide new insights to understand present-day landscape dynamics affecting archaeological heritage [34,35]. The nearly global availability of the SRTM offers the archaeologists the opportunity to have a prompt virtual survey of large areas for the detection and mapping of huge archaeological features such as mounds in the Middle East and the Nazca lines in Peru (Fig. 3). With the start of the TanDEM-X mission, 3D digital models at an unprecedented resolution could be derived for several applications including landscape archaeology and palaeoenvironmental studies [36].

4. Satellite SAR interferometry for monitoring

4.1. General description

The 'radar interferometry' remote sensing technique combines two or more radar images over the same area to detect changes occurring between acquisitions. Interferometry allows for the monitoring of even slight ground movement – down to a few millimetres – across wide areas. Differential Interferometric SAR (DInSAR) techniques date back to 1989 when L-band SEASAT SAR data was first exploited for this purpose [37]. Since 2001, the capability of DInSAR has been considerably improved by using MultiTemporal Interferometric SAR (MT-InSAR) [38–42] adopted to reduce noise and retrieve consistent estimation.

4.2. Cultural heritage monitoring by satellite SAR interferometry

In the last decade, growing interest has been directed towards the exploitation of remote sensing for monitoring cultural heritage using DInSAR as relevant tool for deformation monitoring and preventive diagnosis of monuments and surrounding environments [6]. For example, Parcharidis et al. [43] focused on the ancient Olympic site (Greece) to monitor ground subsidence; Tapete et al. [44] tested the capabilities of MT-InSAR techniques for preventive diagnosis of deformation threatening the structural stability of archaeological monuments in Italy. UNESCO has recommended InSAR for World Heritage site preservation and management. For

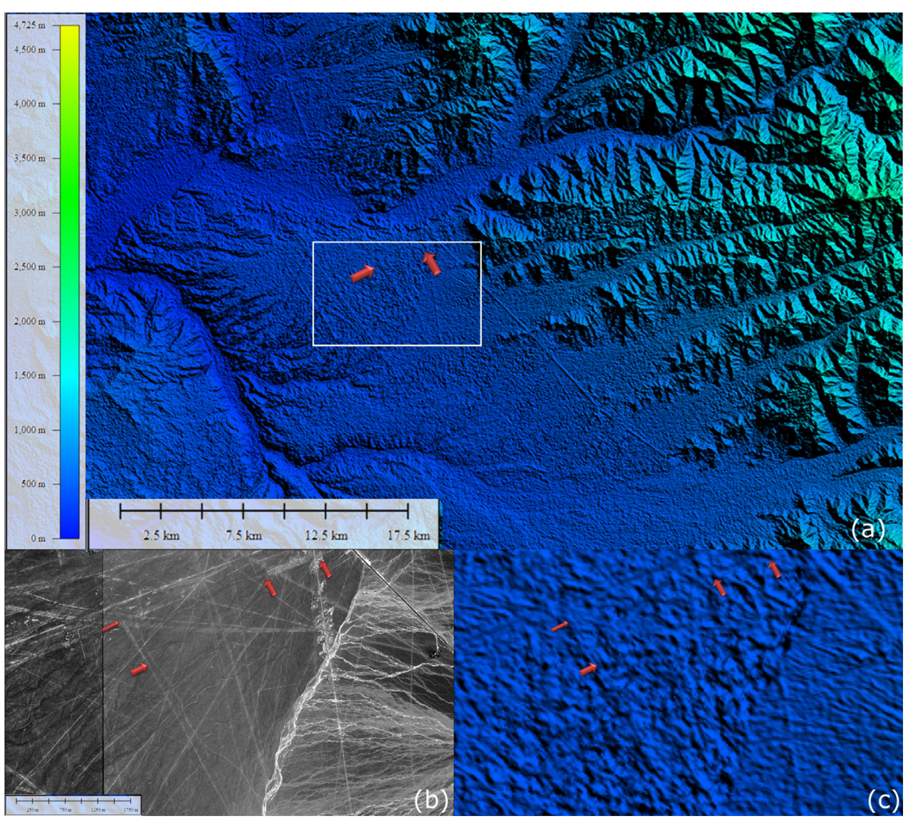

Fig. 3. (a) SRTM at 30 m of geometric resolution: Pampa de Nazca (Peru) famous for the geoglyphs included in the World Heritage list. The images put in evidence a number of linear features which are largely related to roads and tracks of cars which partially destroyed this extraordinary cultural heritage. Some geoglyphs, such as trapezoids, well visible from the panchromatic WorldView2 satellite image (b), could be also observed form the SRTM at 30 m (c).

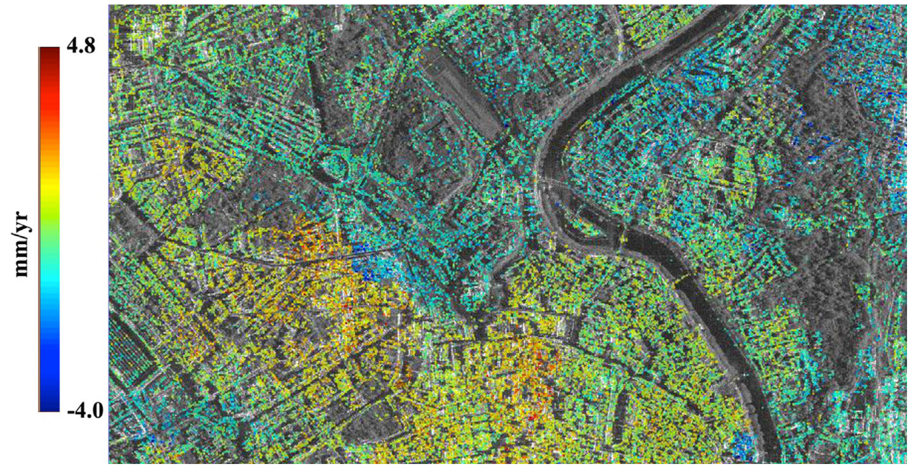

Fig. 4. Historical Centre of Rome: Velocity maps obtained by processing a data set of two interferometric stacks of COSMO-SkyMed Stripmap from March 2011 to June 2014. The image has been processed by P. Milillo.

instance, based on a request from UNESCO, DLR-Germany acquired high-resolution interferometric TerraSAR-X data for monitoring ground subsidence in the ancient Mexico City due to impacts of a complex of anthropogenic activities [45].

Owing to the occurrence of multi-platform and high-resolution data, fine structural monitoring and preventive diagnosis of ancient monuments have become increasingly feasible with the development of the Differential Tomography SAR (D-TomoSAR) and Ground-Based Interferometric SAR (GB-InSAR) technologies. Fornaro et al. [46] applied D-TomoSAR into 4D imaging experiment (3D positioning and 1D deformation velocity) in Rome. Fratini et al. [47] assessed the vibration reduction on the Baptistery of San Giovanni in Florence after vehicular traffic block by analyzing data from a GB-InSAR system. Recently, Cigna et al. [48] carried out a comprehensive study focused on SAR-based investigations on Rome over time. In particular, outputs from X-band COSMO-SkyMed time series processed using the Stanford Method for Persistent Scatterers (StaMPS), confirms the persistence of ground motions affecting monuments, and subsidence in southern residential quarters adjacent to the Tiber River (see Fig. 4).

5. Discussions

The occurrence of multi-mode SAR systems provides abundant images with different spatial-temporal resolutions, bands, incidence angles, polarizations and revisit cycles. Taking the diversity of physical heritage properties and its surroundings into account, it is necessary to develop an application-oriented strategy for the optimal selection of SAR data. Generally, when the incidence angle is constrained, SAR images with a long wavelength are suitable for heritage target detection due to SAR's penetration capability, particularly in dry-alluvial deserts. Polarimetric high-resolution SAR data are ancillary for scattering property identification and the extraction of weak information from heritage targets. For linear ancient remains, the flight path of SAR images should be in parallel with the direction of observed targets for the formation of dihedral and helix scatterings based on the theory of radar physics, which is beneficial for improved detection of potential targets. When the spatial distribution and dominant direction of heritage targets are unknown, multi-angle observations are recommended for a comprehensive analysis. For heritage sites monitoring and preventive diagnosis, the landscape and dimension should be considered in the selection of SAR data. In general, SAR data with a long wavelength are recommended for natural areas (i.e. Geoparks and Natural reserves) covered by vegetation in order to enhance capabilities of penetration and coherence maintenance; in contrast, SAR data with a short wavelength are preferred in settlement regions in order to enhance the accuracy of estimated deformations using DInSAR or MT-InSAR models (the accuracy of InSAR-derived deformation is inversely proportional to the wavelength). Median-resolution spaceborne SAR data are recommended for large-scale heritage sites to reflect the entire landscape and its spatial-temporal patterns; while for a specific local-scale ancient settlement, high-resolution SAR data are preferred for fine monitoring and preventive diagnosis.

6. Conclusions

For the ease of understanding, this paper reviews the state-of-the-art of spaceborne SAR remote sensing for archaeology from aspects of the mechanisms and characteristics of sensors. Two potential applications are further emphasized:

- new-heritage detection and discovery;
- existing-heritage monitoring and diagnosis, taking advantage of the merits of SAR remote sensing in terms of penetration, polarization and interferometry.

Optimization of SAR data is discussed, providing insights into promotion of the technology for archaeological studies.

It is time to make SAR operative for archaeological research; however, the challenge is intriguing as well as difficult. The coupling mechanism of surface roughness, incidence angle and the scattering and propagation mechanism of SAR signals, interacting with heritage targets beneath the surface should be investigated in detail in order to establish SAR image interpretation rules for archaeology. To this aim it is desirable to apply SAR technology to more studies and investigations on an increasing variety of archaeological typologies and their environs with ground truth validations. The COSMO-SkyMed data of Fig. 4 were provided by the Italian Space Agency under license agreement from Archeocosmo.

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References

[1] R. Lasaponara, N. Masini, Satellite synthetic aperture radar in archaeology and cultural landscape: an overview, Archaeol. Prospection 20 (2013) 71–78.
[2] F. Chen, H. Lin, S. Cheng, Principle, method and application of spaceborne Synthetic Aperture Radar interferometry and time-series analysis, Science Press, Beijing, 2013 (in Chinese).
[3] G. Franceschetti, R. Lanari, Synthetic aperture radar processing, CRC Press, London, 1999.
[4] N. Dore, J. Patruno, E. Pottier, M. Crespi, New research in polarimetric SAR technique for archaeological purposes using ALOS PALSAR data, Archaeol. Prospection 20 (2013) 79–87.
[5] T.G. Garrison, B. Chapman, S. Houston, E. Roman, J.L.G. Lopez, Discovering Ancient Maya settlements using airborne radar elevation data, J. Archaeol. Sci. 38 (2011) 1655–1662.
[6] W. Zhou, F.L. Chen, H.D. Guo, Differential radar interferometry for structural and ground deformation monitoring: a new tool for the conservation and sustainability of cultural heritage sites, Sustainability 7 (2015) 1712–1729.
[7] A. Traviglia, D. Cottica, Remote sensing applications and archaeological research in the Northern Lagoon of Venice: the case of the lost settlement of Constanciacus, J. Archaeol. Sci. 38 (2011) 2040–2050.
[8] M. Noviello, M. Ciminale, V.D. Pasquale, Combined application of pansharpening and enhancement methods to improve archaeological cropmak visibility and identification in QuickBird imagery: two case studies from Apulia, Southern Italy, J. Archaeol. Sci. 40 (2013) 3604–3613.
[9] C. Bassani, R.M. Cavalli, R. Goffredo, A. Palombo, S. Pascucci, S. Pignatti, Specific spectral bands for different land cover contexts to improve the efficiency of remote sensing archaeological prosection: the Arpi case study, J. Cult. Herit. 10 (2009) e41–e48.
[10] N. Masini, R. Lasaponara, Investigating the spectral capability of QuickBird data to detect archaeological remains buried under vegetated and not vegetated areas, J. Cult. Herit. 8 (2007) 53–60.
[11] F. Chen, N. Masini, R. Yang, P. Milillo, D. Feng, R. Lasaponara, A space view of radar archaeological marks: first applications of COSMO-SkyMed X-Band Data, Remote Sensing 7 (2015) 24–50.
[12] O.G.S. Crawford, Air photography for archaeologists, ordnance survey professional papers, new series, 12, HMSO, Southampton, 1929.
[13] J. Dassie, Manuel d'archéologie aérienne, Éditions Technip, Paris, 1978.
[14] N. Masini, R. Lasaponara, Investigating the spectral capability of QuickBird data to detect archaeological remains buried under vegetated and not vegetated areas, J. Cult. Herit. 8 (1) (2007) 53–60.
[15] C. Stewart, A. Di Iorio, G. Schiavon, Analysis of the utility of Comso Skymed stripmap to detect buried archaeological features in the region of Rome. Experimental component of WHERE project, in: R. Lasaponara, N. Masini, M. Biscione (Eds.), Earth Observation and Social Perspectives. Towards Horizon 2020. Proceedings of the 33rd EARSeL Symposium., EARSeL and CNR publisher, Matera (Italy), 2013, pp. 203–212.
[16] J.F. McCauley, G.G. Schaber, C.S. Breed, M.J. Grolier, C.V. Haynes, B. Issawi, C. Elachi, R. Blom, Subsurface valleys and geoarchaeology of the eastern Sahara revealed by shuttle radar, Science 218 (1982) 1004–1020.
[17] F. El-Baz, Prehistoric artifacts near paleo-channels revealed by radar images in the western desert of Egypt, in: Remote Sensing in Archaeology from Spacecraft, Aircraft, on Land, and in the Deep Sea, Boston University, Boston, USA, 1998.
[18] D.H. Holcomb, I.L. Shingiray, Imaging SAR in archaeological investigations: an image processing perspective, in: J. Wisemann, F. El-Baz (Eds.), Remote Sensing in Archaeology, Springer-Verlag, Berlin, 2007, pp. 11–45.
[19] H. Guo, Spaceborne multifrequency, polarametric and interferometric radar for detection of the targets on earth surface and subsurface, J. Remote Sensing 1 (1997) 32–39 (in Chinese).
[20] R. Blom, R. Crippen, C. Elachi, Detection of subsurface features in SEASAT SAR images of means valley, Mojave Desert, California, Geology 12 (1984) 346–349.
[21] R. Blom, N. Clapp, J. Zarins, G. Hedges, Space technology and the discovery of the Lost City of Ubar, Paper read at IEEE Aerospace Conf, 1997.
[22] R.E.W. Adams, Swamps, canals, and the locations of Ancient Maya Cities, Antiquity 54 (212) (1980) 206–214.
[23] R. Adams, W. Brown, T. Culbert, SAR mapping, archeology, and Ancient Maya land use, Science 213 (1981) 1457–1463.
[24] K.O. Pope, B.H. Dahlin, Ancient Maya Wetland agriculture: new Insights from ecological and remote sensing research, J. Field Archaeol. 16 (1989) 87–106.
[25] K.O. Pope, B.H. Dahlin, SAR detection and ecology of Ancient Maya canal systems: reply to Adams et al, J. Field Archaeol. 20 (1993) 379–383.
[26] T.L. Sever, D.E. Irwin, Remote-sensing investigation of the Ancient Maya in the Peten Rainforest of Northern Guatemala, Anc. Mesoamerica 14 (2003) 113–122.
[27] F.B. Richason III., C. Hritz, The use of digitally enhanced SARsat SAR imagery in the interpretation of archaeological sites in the Nippur, Iraq, area of the Lower Mesopotamian Plain, in: Proceedings of the International Conference on Remote Sensing in Archaeology from Spacecraft, Aircraft, on Land and in the Deep Sea, Boston, 1998.
[28] D. Evans, C. Pottier, R. Fletcher, S. Hensley, I. Tapley, A. Milne, M. Barbetti, A comprehensive archaeological map of the world's largest preindustrial settlement complex at Angkor, Cambodia, Proc. Nat. Acad. Sci. 104 (2007) 14277–14282.
[29] E. Moore, T. Freeman, S. Hensley, Spaceborne and airborne SAR at Angkor. Introducing new technology to the ancient site, in: J. Wisemann, F. El-Baz (Eds.), Remote Sensing in Archaeology, Springer-Verlag, Berlin, 2007, pp. 185–216.
[30] D. Tapete, F. Cigna, N. Masini, R. Lasaponara, Prospection and monitoring of the archaeological heritage of Nasca, Peru, with ENVISAT ASAR, Archaeol. Prospection 20 (2013) 133–147.
[31] C. Stewart, R. Lasaponara, G. Schiavon, ALOS PALSAR analysis of the archaeological site of Pelusium, Archaeol. Prospection 20 (2013) 109–116.
[32] J. Patruno, R. Dore, M. Crespi, E. Pottier, Polarimetric multifrequency and multi-incidence SAR sensors analysis for archaeological purposes, Archaeol. Prospection 20 (2013) 89–96.
[33] R. Linck, T. Busche, S. Buckreuss, J.W.E. Fassbinder, S. Seren, Possibilities of archaeological prospection by high-resolution X-band satellite radar-a case study from Syria, Archaeol. Prospection 20 (2013) 97–108.
[34] F.C. Conesa, N. Devanthéry, A.L. Balbo, M. Madella, O. Moserrat, Use of satellite SAR for understanding long-term human occupation dynamics in the monsoonal semi-arid plains of North Gujarat, India, Remote Sensing 6 (11) (2014) 11420–11443.
[35] F. Bachofer, G. Quénéhervé, M. Märker, The Delineation of Paleo-Shorelines in the Lake Manyara Basin Using TerraSAR-X Data, Remote Sensing 6 (3) (2014) 2195–2212.
[36] S. Erasmi, R. Rosenbauer, R. Buchbach, T. Busche, S. Rutishauser, Evaluating the Quality and Accuracy of TanDEM-X Digital Elevation Models at Archaeological Sites in the Cilician Plain, Turkey, Remote Sensing 6 (10) (2014) 9475–9493.
[37] X. Zhou, N.B. Chang, L. Shusun, Applications of SAR interferometry in earth and environmental science research, Sensors 9 (2009) 1876–1912.
[38] A. Ferretti, C. Prati, F. Rocca, Nonlinear subsidence rate estimation using persistent scatterers indifferential SAR interferometry, IEEE Trans. Geosci. Remote Sensing 38 (2000) 2202–2212.
[39] A. Hooper, A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches, Geophys. Res. Lett. 35 (2008) L16302.
[40] A. Ferretti, A. Fumagalli, F. Novali, C. Prati, F. Rocca, A. Rucci, A new algorithm for processing interferometric data-stacks: SqueeSAR, IEEE Trans. Geosci. Remote Sensing 49 (2011) 3460–3470.
[41] R. Lanari, O. Mora, M. Manunta, A small-baseline approach for investigating deformations on full-resolution differential SAR interferograms, IEEE Trans. Geosci. Remote Sensing 42 (2004) 1377–1386.
[42] F. Chen, H. Lin, W. Zhou, T. Hong, G. Wang, Surface deformation detected by ALOS PALSAR small baseline SAR interferometry over permafrost environment of Beiluhe section, Tibet Plateau, China, Remote Sensing Environ. 138 (2013) 10–18.
[43] I. Parcharidis, M. Foumelis, K. Pavlopoulos, P. Kourkouli, Ground deformation monitoring in cultural heritage areas by time series SAR interferometry: the case of ancient Olympia site (western Greece), in: Proceedings of Fringe 2009 Workshop, Frascati, Italy, 30 Nov., to 4 Dec., (ESA SP, 677, March 2010), 2009.
[44] D. Tapete, R. Fanti, R. Cecchi, P. Petrangeli, N. Casagli, Satellite radar interferometry for monitoring and early-stage warning of structural instability in archaeological sites, J. Geophys. Eng. 9 (2012) 10–25.
[45] http://www.unesco.org/science/remotesensing/?id_page=147&lang=en
[46] G. Fornaro, F. Serafino, 4-D SAR imaging: the case study of Rome, IEEE Geosci. Remote Sensing Lett. 7 (2010) 236–240.
[47] M. Fratini, M. Pieraccini, C. Atzeni, M. Betti, G. Bartoli, Assessment of vibration reduction on the Baptistery of San Giovanni in Florence (Italy) after vehicular traffic block, J. Cult. Herit. 12 (2011) 323–328.
[48] F. Cigna, R. Lasaponara, N. Masini, P. Milillo, D. Tapete, Persistent Scatterer Interferometry Processing of COSMO-SkyMed StripMap HIMAGE Time Series to Depict Deformation of the Historic Centre of Rome, Italy, Remote Sensing 6 (2014) 12593–12618.