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Trends and perspectives of space-borne SAR remote sensing for archaeological landscape and cultural heritage applications

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ABSTRACT

This paper provides an overview of the opportunities that image analysts, archaeologists and conservation scientists currently have to use space-borne Synthetic Aperture Radar (SAR) imagery for prospection of cultural landscapes and investigation of environmental, land surface and anthropogenic processes that can alter the condition of heritage assets. The benefits of the recent developments in SAR satellite sensors towards higher resolution (up to less than 1 m) and shorter revisiting times (up to a few days) are discussed in relation to established techniques using the two key SAR parameters – amplitude and phase. Selected case studies from Middle East to South America illustrate how SAR can be effectively used to detect subtle archaeological features in modern landscapes, monitor historic sites and assess damage in areas of conflict. These examples form the basis to highlight the current trends in archaeological remote sensing based on space-borne SAR data in the era of the European Space Agency's Sentinel-1 constellation and on-demand high resolution space missions such as TerraSAR-X.

1. Introduction

This paper aims to provide an overview on the use of Synthetic Aperture Radar (SAR) images acquired from space for purposes of archaeological landscape studies and cultural heritage applications, in recognition of the increasing role that this branch of remote sensing plays in the field of archaeological science.

Recent reviews have been published to illustrate the basic principles that make SAR suitable for archaeological prospection (Lasaponara and Masini, 2013; Chen et al., 2015a) and showcase some successful achievements with high resolution SAR sensors (Chen et al., 2015b). But an assessment of the current trends in SAR archaeological remote sensing has not been carried out yet, alongside a review of the existing opportunities offered by the recent technological developments.

It is to fill this gap that in this paper we review the three key factors – data, processing methods and application types – that at present favour the exploitation of this space technology to complement well-established techniques of aerial photography, optical remote sensing and generation of digital elevation models (DEMs).

2. Background and growing impact

From an historical perspective, the earliest use of SAR to study paleo-landscapes dates back to the 1980s with investigations in both tropical and subtropical territories (Adams et al., 1981) and arid environments (Elachi et al., 1984). Since then, several studies revealed hidden features and paleo-landscapes, by exploiting the peculiar penetration capability of the radar signal (El-Baz, 1998; Lira et al., 2005; Wiseman and El-Baz, 2007; Evans et al., 2007; Moore et al., 2007) at the different microwave bands of acquisition, i.e. *L* 1–2 GHz, 15–30 cm; *C* 4–8 GHz, 3.75–7.5 cm; *X* 8–12.5 GHz, 2.5–3.75 cm, and proving that better performance is usually obtained at longer wavelengths (e.g. L-band) and in drier and fine-grained soils.

A proof of evidence of the growing scientific relevance that SAR is assuming in this field is gathered in Fig. 1. Using a similar approach to that described by Agapiou and Lysandrou (2015) a Scopus engine search of the keywords 'radar', 'remote sensing', 'archaeology', 'cultural heritage' and 'polarimetry', highlights that there has been a significant increase of indexed peer-reviewed publications focussed on the use of SAR for archaeological science in the last 30 years (series "Total" in Fig. 1). A steady increase is observed until 2011, while a publication boost occurred in 2013 with the publication of a dedicated special issue on *Archaeological Prospection*. Although this search is not exhaustive (and does not pretend to be so), it provides an interesting and objective bibliometric. The analysis of authors' affiliations also reveals that one

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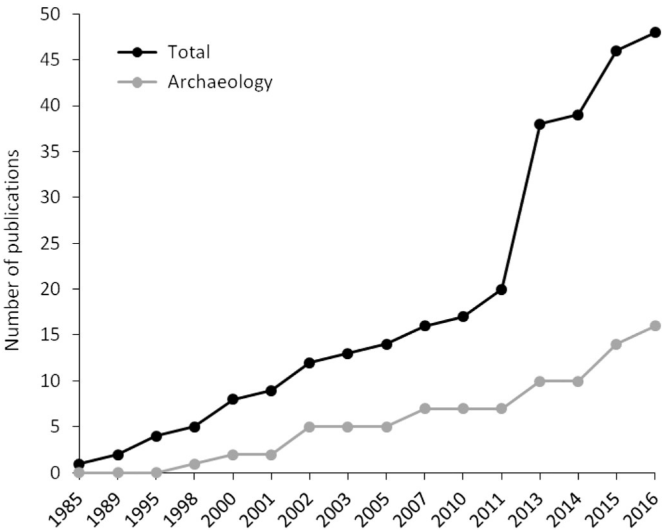

Fig. 1. Graph of publications (series "Total") since 1985 that are indexed in Scopus and specifically use SAR for studies of archaeological landscapes, archaeological prospection and condition assessment of cultural heritage. The series "Archaeology" refers to those publications among the "Total" that are co-authored by archaeologists.

third of the total number of these publications has involved research teams including archaeologists (series "Archaeology" in Fig. 1), and confirms that teamwork between archaeologists and remote sensing experts is increasing since the late 1990s.

Matching evidence is found in Agapiou and Lysandrou (2015) who report that 'radar images' are among the most frequently used terms in the relevant remote sensing literature between 2013 and 2015.

The large percentage of the published research is based on the use of the 'amplitude', i.e. the magnitude of the microwave wavelength recorded for each pixel of the complex SAR image. The 'radar backscatter' is the portion of the outgoing radar signal recorded over successive pulses from elements of a synthetic aperture to create the image, and is mostly analysed to infer the compositional and soil moisture properties of the radar targets on the ground and associate them to surface changes that may relate to buried features.

The other main group of publication concentrates on the use of DEMs generated with Interferometric SAR (InSAR) techniques, by which the measured differences in the phase of the return signal between two satellite passes is used to combine two radar acquisitions of the same area of the Earth's surface, taken from slightly different angles, to generate accurate height maps (ESA, 2015).

3. Current opportunities from space

The scientific advancement of satellite radar research for archaeological studies was possible owing to an increasing availability, from the early 1990s, of SAR imagery in the catalogues of the space agencies, covering with more regular frequency not only the Western countries but also remote areas of South America, Asia and Africa. Furthermore, since the early 2000s, the beam modes with which SAR images are acquired have been continuously improved, so that nowadays image analysts, archaeologists and conservation scientists can access data with: wide-swath to spotlight coverage, kilometre to sub-metre spatial resolution, historical and present dates of acquisition, longer to shorter wavelength (L/C/X bands), monthly to daily revisiting time if collecting time series.

At present radar remote sensing is witnessing the revolutionary turn of the satellites from the first (e.g., ERS-1/2, ENVISAT, ALOS, RADARSAT-1/2) to the second generations (e.g., TerraSAR-X, COSMO-SkyMed, Sentinel-1 and ALOS-2). In this context there is a range of opportunities for feature detection, condition and damage assessment (Tapete et al., 2015c, 2016).

3.1. Space-borne data

3.1.1. Legacy SAR archives

The ERS-1/2 and ENVISAT catalogues of the European Space Agency (ESA) are the most complete and abundant archives of C-band time series, with almost uninterrupted temporal coverage from 1991 to April 2012. Their Image Mode spatial resolution of 25–30 m and swaths of 100 km make these images suitable for wide-area and regional assessments (e.g. detection of paleo-channels, trade route reconstruction), alongside investigation of sites as wholes and contextualised in their surrounding environments (Fig. 2a).

Similarly, the archives built by the Japanese Space Agency (JAXA) with the L-band ALOS PALSAR sensor provide an historical view of cultural landscapes from 2006 to May 2011, with resolution up to 7 m in Fine Beam mode, both single and dual polarised (HH, VV, HH + HV, VV + VH). Kurtcebe et al. (2010) and Guo et al. (2011) are among the earliest studies showcasing the usefulness of ALOS PALSAR in archaeology, while more research may be carried out to fully exploit the archives available over those regions in India, South America and Pacific Ocean where ancient civilizations settled and flourished for centuries.

3.1.2. New satellites and SAR imaging modes

The TerraSAR-X constellation of the German Aerospace Center (DLR) is a clear example of how on-demand high to very high resolution SAR can nowadays support studies of archaeological landscapes and sites by providing a range of different resolutions, up to unprecedented sub-metre level imaging.

Acquiring X-band imagery since mid-2007 with the twin satellite TanDEM-X launched three years later, TerraSAR-X (TSX) is building an image archive with repeat cycle of 11 days (i.e. a third of ESA's first generation sensors) and a range of spatial resolutions, from 16 m and scene size of 100 km (width) × 150 km in ScanSAR mode, to azimuth resolution of 0.24 m over scene extent varying between 2.5 to 2.8 km in azimuth and 4.6 to 7.5 km in range in Staring Spotlight mode (Mittermayer et al., 2014).

The Hellenistic town of Apamea, Syria, well demonstrates the paradigm of multi-temporal and multi-scale analysis using different satellites. ScanSAR time series 2011–2014 (Fig. 2b) complemented the historical analysis with ERS-1/2 and ENVISAT by providing a regional scale coverage to assess the recent impact on landscape due to the construction of the dam nearby the Justinian walls (see Section 3.2.4) and the agricultural activities in the Ghab plain (Fig. 2a). Coeval sub-metre resolution Staring Spotlight imagery (Fig. 2c; Tapete et al., 2016), instead, allows up-scaling of the observations at the level of individual structures, such as the monumental colonnade of Apamea (Fig. 2d). Given the current exposure of the site to war damages, looting and vandalism, the strong backscatter return from the marble columns provides a reliable SAR marker to assess whether the ancient ruins are still standing or collapsed.

Archaeologists can also benefit from the full range of beam modes and incidence angles offered by the same satellite mission to improve the detection and delineation of subtle archaeological features, while relating them to the landscape over a wide swath. Fig. 3 demonstrates the stunning improvement in SAR imaging from ScanSAR to High Resolution Spotlight modes to discriminate the UNESCO World Heritage List Nasca Lines, in Southern Peru. The distinctive radar signature of the 'negative geoglyphs' (exposed unpatinated and lighter coloured ground) can be analysed by drawing a backscatter profile from the feature to the nearby soil (dark gravels) and checking its consistency or variations by year or by season (Tapete et al., 2013b).

The suitability of SAR remote sensing to the specific purpose of investigating archaeological landscapes relies on the flexibility offered by the radar sensors to tune up the acquisition parameters. In this

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