International Journal of Applied Earth Observation and Geoinformation 28 (2014) 211–219

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

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

Multi-frequency, polarimetric SAR analysis for archaeological prospection

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ARTICLE INFO

Article history:
Received 18 March 2013
Accepted 13 November 2013

Keywords:
Archaeology
SAR
PALSAR
Radarsat-2
Prospection
Polarimetry

ABSTRACT

The aim of this study is to assess the sensitivity to buried archaeological structures of C- and L-band Synthetic Aperture Radar (SAR) in various polarisations. In particular, single and dual polarised data from the Phased Array type L-band SAR (PALSAR) sensor on-board the Advanced Land Observing Satellite (ALOS) is used, together with quadruple polarised (quad pol) data from the SAR sensor on Radarsat-2. The study region includes an isolated area of open fields in the eastern outskirts of Rome where buried structures are documented to exist. Processing of the SAR data involved multitemporal averaging, analysis of target decompositions, study of the polarimetric signatures over areas of suspected buried structures and changes of the polarimetric bases in an attempt to enhance their visibility. Various ancillary datasets were obtained for the analysis, including geological and lithological charts, meteorological data, Digital Elevation Models (DEMs), optical imagery and an archaeological chart.

For the Radarsat-2 data analysis, results show that the technique of identifying the polarimetric bases that yield greatest backscatter over anomaly features, and subsequently changing the polarimetric bases of the time series, succeeded in highlighting features of interest in the study area. It appeared possible that some of the features could correspond with structures documented on the reference archaeological chart, but there was not a clear match between the chart and the results of the Radarsat-2 analysis. A similar conclusion was reached for the PALSAR data analysis. For the PALSAR data, the volcanic nature of the soil may have hindered the visibility of traces of buried features. Given the limitations of the accuracy of the archaeological chart and the spatial resolution of both the SAR datasets, further validation would be required to draw any precise conclusions on the sensitivity of the SAR data to buried structures. Such a validation could include geophysical prospection or excavation.

1. Introduction

Remote sensing is a recognised asset to archaeological surveys. While ground based sensing techniques are capable of identifying buried structures and are neither invasive nor destructive (Jones, 2008), their application over large areas is both costly and time consuming. Remote sensing techniques offer the advantage of providing a synoptic view, covering large areas, and demonstrating the capability to detect features not easily visible on the ground that may be important for archaeological applications (Brivio et al., 2000). Moreover, a range of instruments and techniques can be used in remote sensing surveys including aerial photography, multi and hyperspectral imaging, thermal imaging, LIDAR (LIght Detection And Ranging), photogrammetry and SAR based techniques.

SAR has various properties that can be exploited for archaeological prospection. The fact that SAR is an active sensor measuring microwave backscatter makes it sensitive to differences in surface roughness which can be seen as variations of brightness and texture in images of SAR backscatter amplitude (Ford et al., 1983; Holcomb and Shingiray, 2007; Cigna et al., 2013; Tapete et al., 2013). This property has aided the discovery of archaeological sites (e.g. Blom et al., 1997; Holcomb, 2001; Moore et al., 2006). SAR backscatter is very much dependent on the dielectric properties of targets, such as soils, a major contributing factor of which is the soil moisture content (Ulaby et al., 1982; Holcomb and Shingiray, 2007). This property has been exploited for archaeological prospection identifying moisture anomalies indicating the presence of sites of archaeological interest (e.g. Moore et al., 2006). It has also been determined that depending on certain conditions, transmission of the microwave field can take place through a target medium (Ulaby et al., 1982; Morrison, 2013). One condition that affects the depth of penetration is the dielectric constant of the medium (Ulaby et al., 1982). Another condition is wavelength of the microwave field, with longer wavelengths providing further

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http://dx.doi.org/10.1016/j.jag.2013.11.007

penetration (Ulaby et al., 1982; Schaber, 1999; Schaber and Breed, 1999). This property has been put into practice for the study of ancient landscapes, which has led to the discovery of ancient palaeorivers in the Sahara (McCauley et al., 1982), and has explained the existence of ancient anthropological remains in this region (El-Baz et al., 2007). It has also been used to directly detect archaeological structures buried beneath the ground in arid regions such as in Syria using TerraSAR-X (Linck et al., 2013) and Egypt using ALOS PALSAR (Stewart et al., 2013). DEMs derived from SAR interferometry from both airborne and spaceborne sensors have been used for direct detection of archaeological sites (e.g. Sever and Irwin, 2003) and for indirect detection through landscape analysis (Evans and Farr, 2007). Finally, the ability to fully characterise the SAR backscatter polarisation is another property that has been utilised for archaeological applications (e.g. Moore and Freeman, 1996; Dore et al., 2013; Patruno et al., 2013).

Until relatively recently, the coarse spatial resolution of spaceborne SAR sensors has meant that their utility for archaeological surveys has mainly been in the indirect analysis of the geographical context, rather than in the direct identification of sites. Only with airborne data was it possible to achieve high enough resolution for direct detection of buried structures. Now this is changing, with the new generation of spaceborne SAR missions that are capable of acquiring data at 1 m spatial resolution in spotlight modes. While quad pol acquisition modes are still considered experimental, much quad pol data exists, albeit at reduced spatial resolution in comparison to single or dual pol modes. It is now possible to undertake a fully polarimetric analysis of high resolution spaceborne SAR at multiple frequencies (from X to L band).

The aim of the study presented in this paper is to explore the capabilities offered by this new generation of high resolution sensors for archaeological prospection in a relatively small area of interest in the outskirts of Rome, Italy. Time series of quad pol Radarsat-2 data and single and dual pol ALOS PALSAR data have been obtained for the analysis, thus enabling a comparison to be made between C and L band at multiple polarisations over time.

The area of interest was chosen for its size, the smoothness of its landscape (without many buildings, trees, etc.), and for the high density of buried archaeological sites that are reported to exist in the area (Quilici, 1974).

1.1. Rationale for archaeological prospection with Radarsat-2

The rationale for the use of Radarsat-2 FQ (Fine Quad) data is that the additional information provided by the four separate polarisations of the C-band SAR backscatter may be sufficient to detect proxies indicating the existence of buried archaeological features.

Buried features may affect the properties of the overlying soil, including moisture content and composition. These in turn can affect any vegetation that grows on the surface. Soil overlying buried features that are close to the surface may not be deep enough to allow vegetation to place deep roots (Lasaponara and Masini, 2012). These differences in the soil and vegetation over buried structures compared to where there are no buried structures may be sufficiently great to enable their detection on remotely sensed imagery. It has already been shown that optical imagery can be used to detect such anomalies (Jones and Evans, 1975). It is hypothesised that it may also be possible to detect these features on quad pol SAR imagery through analysis of the backscatter signature, taking advantage of the sensitivity of microwaves to soil moisture (Fung and Ulaby, 1983) and the sensitivity of SAR to the scattering mechanism of targets (Boerner et al., 1998), which may differ over buried features due to differences in the type and health of vegetation overlying them.

1.2. Rationale for archaeological prospection with ALOS PALSAR

ALOS PALSAR was chosen to assess whether the long wave SAR signal (L-band) is capable of directly detecting buried archaeological structures by passing through the overlying soil, given the right conditions.

In SAR imaging, usually terrain scattering includes both surface and volume scattering components. In surface scattering, the scattering strength is proportional to the relative complex dielectric constant of the surface, and the pattern of angular scattering is determined by the surface roughness. In volume scattering, the scattering strength is proportional to the dielectric discontinuities inside the medium and the density of the embedded inhomogeneities (or the variance of the fluctuating dielectric function for a continuous random medium), and the pattern of angular scattering is determined by the roughness of the boundary surface, the average dielectric constant of the medium, and the geometric size of the inhomogeneities relative to the incident wavelength (or the correlation length of the fluctuating dielectric function for a continuous random medium) (Ulaby et al., 1982).

Considering that the presence of water in soils is one of the main factors determining its average dielectric constant, it is hypothesised that in very dry periods, such as a typical Italian summer, conditions may be favourable over the study area for some penetration of the microwave field into the soil sufficient to reach buried features.

Ulaby et al. (1982) also showed that if λ is the wavelength and $\varepsilon = \varepsilon' - j\varepsilon''$ is the relative complex dielectric constant, for materials with $\varepsilon''/\varepsilon' < 0.1$, the penetration depth δ_P of a SAR signal through a volume can be approximated as:

Eq. (1) Penetration depth of electromagnetic waves (Ulaby et al., 1982)

$$\delta_P = \frac{\lambda\sqrt{\varepsilon'}}{2\pi\varepsilon''}$$

According to this expression, the greater the wavelength, the greater the penetration depth. ALOS PALSAR was chosen for the long wavelength of the microwave field employed by the sensor (L-band, 23.6 cm). No other spaceborne SAR systems exist that can provide high resolution data over the area of interest in L-band. Current spaceborne SAR systems operate in shorter wavelengths of either C-band (5.6 cm) or X-band (3.1 cm).

1.3. Study area

The study area includes a region in the eastern outskirts of Rome situated south of the Via Prenestina and to the east of the Grande Raccordo Anulare, the main ring road around Rome (Fig. 1). This is an isolated area of open fields surrounded by developed land, including the settlements: Colle Prenestino and Colle Monfortani to the North, Prato Fiorito to the East, Valle Fiorita to the South and Tor Bella Monaca and Torre Angela to the West. In this area there is a high density of archaeological sites, both at the surface and buried beneath the ground, documented on the Forma Italiae archaeological chart (Quilici, 1974) (Fig. 2 and Table 1). These sites include roads, aqueducts, villas and other structures. Traces of buried structures are visible on Google Earth imagery (Fig. 1).

The land cover of the area is classed as non-irrigated arable land and permanent grassland (Comune di Roma, 2008a). The lithology is mainly volcanic although there are also strips running diagonally across the area, in a north-west to south-easterly direction, where the lithology is alluvial. The volcanic land contains ignimbrite from pyroclastic flows originating in the Albano volcano district. The soil is rich in crystals of leucite and pyroxene, and contains also tuff, slag, pumice and pozzolans (Comune di Roma, 2008b) (Fig. 3 and Table 2).