Qualitative evaluation of COSMO SkyMed in the detection of earthen archaeological remains: The case of Pachamacac (Peru)

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Article history:
Received 2 October 2015
Accepted 29 December 2015
Available online 7 December 2016

Keywords:
Satellite remote sensing
SAR
COSMO-SkyMed
UAV
Pleides
Earthen archaeology
Magnetometry
Archaeogeophysics
Inca
Pachacamac
Peru

A B S T R A C T
Archaeological prospection of earthen buried structures, namely non-fired sun-dried mud bricks mixed with organic material, is a critical challenge to address. In fact, this building material exhibits a very low geophysical contrast compared to its surroundings and, therefore, earthen structures are very complex to be identified using remote sensing. In order to cope with this issue, in this paper, we focus on the evaluation of satellite X-band radar data (COSMO-SkyMed) capability for detecting earthen buried structures in a desert area. The results obtained from satellite radar data have been validated for a test site in Pachacamac (Peru) by using unmanned aerial vehicle (UAV) and geomagnetic techniques. The test site is outside the fenced protected zone of Pachacamac, today in the tentative UNESCO list. This paper is the first attempt made until now in evaluating the detectability of earthen archaeological remains using satellite Synthetic Aperture Radar (SAR) data. Outcomes from our investigations clearly point out that the approach we adopted can be useful applied for preventive archaeology and for the planning of future excavation campaigns.

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1. Research aims

In the field of archaeological prospecting, a challenge of great importance and utility is the detection of features related to the presence of deep and shallow buried structures made of earth, that characterize a large amount of archaeological sites of different ages and civilizations all over the world.

The paper shows the first results of the application of X-band COSMO-SkyMed data in an Inca test site of Pachacamac (Peru), characterized by the presence of a wall in adobe, partially emerging and for the rest barely visible (as micro-relief) or buried under sand.

In this paper, the integrated use of diverse remote sensing tools, as optical satellite pictures, geomagnetic techniques and aerial surveys using drone, made it possible to qualitatively evaluate the X-band COSMO-SkyMed data capability in the identification of earthen archaeological features in the desert area of Pachacamac.

2. Experimental

2.1. Introduction

The digital tools nowadays available for archaeology enable us to get extremely precise results speeding up the work during the diverse phases of archaeological investigations ranging from survey, mapping, excavation, documentation and monitoring, moving from artifact to landscape scale. In particular, the use of satellite radar data in archaeological investigations can offer great potential for site detection, especially in desert areas, where optical data are generally strongly limited for the identification of subtle micro-relief due to the shadow as well as for the detection of buried remains due to the absence of the archaeological vegetation marks [1,2].

Even if today a huge amount of SAR data are available, they are still underexploited in the archaeological operative practice. One of the main reasons for the underuse of radar technology is linked to the difficulty in interpreting the data, even though they are finely processed, and thus generating skepticism among archaeologists,

http://dx.doi.org/10.1016/j.culher.2015.12.010
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and the belief that the complexity of this technology is not proportional to its real usefulness in archaeology. Efforts are needed for improving the ability to interpret the radar data, with the support of archaeological data source and additional information obtainable by other remote sensing methods [3].

Therefore, this work provides a first contribution in evaluating the potential of X-band satellite radar data in archeology by using other remote sensing techniques. We focus our attention on the joint use of a fully finished Geocoded Cosmo SkyMed product with the detailed topography, obtained by processing aerial photographs captured from UAVs, and magnetic maps, for detecting adobe remains in a desert area of Pachacamac, which is one of the largest archaeological sites of Peru. For more than 2000 years, Pachacamac was one of the main centers of religious cult keeping this role unchanged in different historical periods and for different cultures such as Chavin, Lima, Huari, Ychma and Inca (for the historical overview the reader is referred to paragraph 2.2.2) [4]. A test site was selected for our investigations. It includes very thick walls built in adobe, which are part of an ancient city wall, enclosing a residential area and cemeteries, dating back to a period ranging from Ychma to Inca ages. With such regard, it is reasonable to believe that a larger part of the wall is under the current ground level, the rest is shallow or emerging.

The paper shows the results of a multiscale and multisensor approach, including satellite optical and SAR remote sensing, geomagnetic prospection and UAV, aimed at quantitatively evaluating the capability of X-band COSMO SkyMed data in detecting buried remains to the ancient earthen walls.

2.2. Pachacamac: history and state of the art of investigations

2.2.1. Brief historical overview

Pachacamac is located on a desert hill about 31 km South East of Lima, on the right bank of Lurin river near its mouth, 800 meters from the Pacific Ocean (Fig. 1). The site covers a total area of around 465 hectares, among which the 30% is occupied by monuments such as temples, pyramids with ramp and palaces.

The first human settlements in the area of Pachacamac date between the end of the Initial Period and the beginning of the Early Horizon (1000-800 BC) at the age of Chavin culture, which developed until the 2nd century BC. The first monument is the so-called Templo de los Adobitos (or Lima Temple), made by small bricks of adobe, which is attributed to the Lima Culture (100-650 AD). Under Huari (650-900 AD) Pachacamac reached its apogee. The sanctuary area became a city also as administrative center of great importance throughout the Andes. The Huari influence can be seen in ceramic objects, paintings and architecture (an example is the "Painted Temple", see 4 in Fig. 2).

The Ychma (900-1450 AD) civilization followed after the collapse of Huari. During the Ychma period Pachacamac continued its expansion becoming a city-state and, later, the capital, known as Ychma, of a region which included the river valleys of Rimac and Lurin. The most important witnesses of the presence of Ychma culture could be found in the architecture, with the so-called “pyramids with ramp” [4], and in the urban structure which was completely renovated and structured around two perpendicular road axes oriented along North-South and East-West, respectively. Later, during Inca Empire (1450–1532), the city, renamed Pachacamac, became an important ceremonial and administrative center. The Incas maintained the sacredness of the place and allowed the priests of Pachacamac to continue to profess their religion and their rites. In the 15th century, the Incas built the Temple of the Sun, and the palaces of Acclahuasi, Taurichumpi and other buildings.

With the Ychma, before, and the Incas, after, Pachacamac reached the current extension of the archaeological area, including sectors I and II (for additional information see section 2.2.2). In the same period, further settlements (see sectors III and IV in Fig. 2) including residential area and cemeteries were built at North of the archaeological area.

2.2.2. Archaeological area

Spatially, the archaeological site is divided into four sectors, defined by two concentric walls and two outer walls. The first wall (known also as Holy Wall) defines sector I including the Temple of the Sun, the “Painted Temple”, the Old Temple [5,6] and cemetery, for an extension of 18.8 ha (see 1, 4 and 5 in Fig. 2, respectively). The second wall, defining sector II, contains roads, cemeteries, many squares and courts, pyramid with ramp [7,8], the Acclahuasi and the Taurichumpi Palace. The two above described sectors embrace a total area of around 130 ha.

At North of the archaeological area and the Panamerican road, at South and West of the District of Pachacamac, there is a desert hill of archaeological interest, conventionally divided in two sectors (III and IV).
Sector III, called “outer city”, is extended from the inner to the outer city walls, for an extension of around 90 ha (see Figs. 2 and 3). Herein, the archaeologist Max Uhle found vast residential areas and a cemetery.

Finally, Sector IV is located at North East of Sector III and extends to meet the District of Pachacamac. The North-eastern border is defined by a long and thick earthen wall.

The investigated test site is located between the Sectors III and IV and includes a section of the walls (named wall S) which crosses the desert hill along WSW–ENE direction. The walls are built in adobe and are 3.80–5.70 m thick, about 500 m long, with height ranging from 20 cm to about 6 m. Along the direction of the wall (see red arrows in Fig. 2), there are significant lacking parts whose foundations are reasonably underground. An integrated remote sensing approach including satellite SAR, UAV and geomagnetic prospection has been used to detect features related to shallow buried walls.

3. Integrated remote sensing: tools, data acquisition and processing approaches

The availability of active and passive remote sensing data provides challenging opportunities to improve the extraction of information, from the qualitative and quantitative point of view.

![Fig. 2. Satellite Pleiades true color image (acquired on April 13, 2013) of the Ceremonial centre of Pachacamac composed of 4 sectors: I and II in the archaeological area, III and IV located at North of the archaeological area and Panamericana Sur road. The numbers indicate the main monuments of the archaeological area such as: Sun Temple (1), Taurichumpi Palace (2), Acllahuasi Palace (3), Painted Temple (4), Old Temple (5), Pilgrim’s Plaza (6), Pyramid with ramp I (7). At North, red arrows denote the presence of walls. The first one is located between sectors III and IV (wall S), the second one (wall NE) is at North East near the modern town of Pachacamac. The red box indicates the area of interest within wall S.](image)

![Fig. 3. (a) COSMO-SkyMed StripMap HiMAGE, and (b) Pleiades image of the study area. Red arrows indicate the emerging earthen walls, whereas yellow arrows denote the anomalies visible from satellite radar data. Yellow boxes in Fig. 3b indicate the two regions of interest (ROI1 and ROI2) discussed in detail in section 3.4. The COSMO-SkyMed image has been acquired on January 2, 2012 in StripMap mode, along the descending orbit, right look side, with VV polarization, at 3 m geometric resolution. The data is a Geocoded product (1C level) obtained projecting the SLC (Single-look Complex) product onto a regular grid in a cartographic reference system whose surface is the earth ellipsoid. Pleiades data have been acquired on April 13, 2013. Also in the case of subtle signals which typically characterize deep and shallow buried remains. In Pachacamac, we conducted our investigations using radar and optical satellite data, aerial photographs taken from UAV and magnetic survey.](image)
applications of SAR data for archaeology and palaeoenvironmental studies have been focused on the exploitation of radar penetration capability particularly significant in drought desert areas [9,10]. These applications have been performed using data with L and P bands but acquired at low geometrical resolution; thus limiting their use for archaeological purposes.

Very high resolution satellite radar data (at 1 m) acquired by TerraSAR-X and COSMO-SkyMed have been only recently used for the reconstruction of archaeological moisture marks as well as of microrelief, thanks to its limited penetration capability [11,12]. The reader is referred to some applications of the authors on Metaponto (Italy) and Pelusium (Egypt), as regards moisture marks [13], and Sabratha (Libya) for the microrelief [14].

One of the main problems for archaeological feature extraction in SAR data is the very low signal/noise ratio and the fact that the visibility of archaeological marks is conditioned, as for optical data, by numerous factors, such as vegetation and soil type, humidity content and salinity. A compromise is needed to satisfactory filter out noise component maintaining, at the same time, the subtle signal associated with archaeological features. In fact, speckle noise reduction may be generally beneficial for the archaeological feature extraction, but the use of filtering to reduce noise could also filter out the target.

The above said complexity, linked to the processing and interpretation of radar data, discourages their use for archaeological purposes. For this reason, a fully finished Geocoded COSMO-SkyMed product was used (GEC 1C level). In particular, from the archived data we selected an image acquired on 2 January 2012 in StripMap mode, along the descending orbit, right look side, at 3 m geometric resolution, with VV polarization and incidence angles ranging from 30°-679° to 33°-762° (related to near and far range, respectively).

However, a further refinement noise removal was carried out using Enhanced Lee filters [15,16] along with textural and morphological filters [17]. The former filter typology is more suitable to extract the complementary information available from the statistical indicators (such as, mean, standard deviation coefficient of variation, autocorrelation for lags, etc). Whereas, the latter filter typology, based on mathematical morphology, is more suitable to find discontinuities in surface, changes in material properties and variations in moisture content, etc. Morphological filters [18] are nonlinear image transformations based on morphological operations such as opening, closing or dilation and erosion, which are size and shape sensitive and they are found to be good in making the image sharper.

The results of the processing for the Northern sector of Pachacamac is showed in Fig. 3a and b shows the same scene from true color Pleides image for a visual comparison with the satellite radar one in Fig. 3a.

Comparing the two images, it is possible to observe that radar provides a greater number of features respect to the optical picture, thanks to its sensitiveness to roughness and, in turn, microrelief. They are mainly linked to the presence of dunes and natural relief covered by sand. In both the remote sensing data, the two walls of sectors III and IV (Wall S and Wall NE) are visible. In Fig. 3b, yellow boxes indicate the two regions of interest (ROIs) discussed in detail in section 4.

3.2. Magnetic survey for the detection of archaeological features

The magnetic survey is one of the most important non-destructive investigation techniques widely used in archaeological prospection [19]. It is based on the measurement of small local variations of the earth’s magnetic field due to the presence of buried objects (i.e. man made buried structures). The geomagnetic approach has allowed us a fast large investigation on the studied area with a low time consuming and a high detection check. For the purpose of our investigations, the geomagnetic measurements have been performed using an optical pumping magnetometer G-858 (by Geometrics) in gradiometric configuration, with two magnetic probes set in a vertical direction (1 m each other). This configuration allowed us to remove the diurnal variations of the natural magnetic field. Among the various acquisition modalities provided by the magnetic sensors, the measurements have been performed by a mapped survey mode that allows us to previously specify and visualize the survey area and to move around within the investigated area in a non-continuous fashion by means of regular grids. The magnetic map was obtained by several parallel profiles composing a regular grid with an interspaced line of 1 m and a sampling rate of 10 Hz, providing more than 4000 gradiometric data for an investigated area of about 50 × 50 mq. The survey direction was forced by the instruments used, because the Cesium sensors need a proper orientation at various earth’s field dip angles. Therefore, a useful software (CSAZ by Geometrics) for the location of Pachacamac calculated the best survey direction (South-North) and a precise sensor dip angles [20]. A wide range of processing were applied, in order to obtain the best S/N ratio such as:

- a pass-band filter, to remove high or low frequency components in the survey;
- a despike tool to remove outliers;
- stretch compensation for errors due to inconstant operator walking and tools to remove zig-zag and destripe effects.

In order to highlight the main geomagnetic linear anomalies, the data were further processed using a Kriging interpolator with a linear variogram [21,22].

3.3. UAV for 3D mapping

Compared to traditional aerial archaeology, the UAVs offer several advantages. They are low cost and able to cover large areas in a short time. There are currently a wide range of UAVs. A classification of diverse UAV systems based on size, weight, endurance, range, and flying altitude, is in [23,24]. For the purpose of our investigations a drone Dji Phantom Vision 2 plus, a radio-controlled quadcopter, able to take off and land vertically on any surface, has been used. It has a structure in carbon fiber with a weight of 1242 g, a diameter of 350 mm and a payload of about 500 g. The propulsion is given by four electric motors powered by a battery which allows a flight range of 20–25 minutes in standard condition. The remote control is performed up to a maximum distance of 700 m, with horizontal, vertical and rotation speed ranging from 0.1 to 15 m/s, 0.1 to 6 m/s and 200°/s, respectively. The Phantom 2 Vision Plus is equipped with a 2-axis gimbal very stable and mounting a Dji camera which can shoot video in Full HD and take photos in 14 megapixels.

UAV surveys, performed in sectors III and IV of Pachacamac, aimed at providing:

- the Digital Elevation Model (DEM) of the area in order to observe and interpret further microrelief linked to shallow remains;
- a very detailed model of the walls enabling us to analyze building techniques as well as to interpret the radar signal backscattering behaviour along the wall (Fig. 4).

For the first aim, images were acquired in automatic and zenith mode at a height from 30 to 50 m. For the second one, the images were captured in manual, oblique and nadiral mode, at a height from 8 to 20 m. The processing of aerial photographs has been aimed at reconstructing the 3D geometry from aerial images. This issue has been addressed by using multiple partially overlapped
images processed using Structure from Motions (SfM) approach. The photogrammetric processing of digital images for generating 3D spatial data has been performed by using Photoscan software [25]. The processing has included the following steps:

- the selection and loading of photos, captured with correct overlap requirement (60% of side overlap + 80% of forward overlap) aimed at minimizing blind-zones;
- computation of camera position and orientation for each photo;
- alignment of photos and building of a sparse point cloud;
- generation of dense point cloud model which allows to calculate depth information for each camera position;
- building of 3D model polygonal mesh;
- textured 3D model.

4. Results and discussion

In this section, the results obtained from each remote sensing technology will be discussed one by one. The full exploitation of data provided by the sensors (from aerial, space and ground acquisition) herein used have been fruitfully integrated within a GIS environment for facilitating the integration and interpretation of the heterogeneous data sources.

As evident from Fig. 3(a and b), the radar scene shows numerous anomalies, many of them clearly referable to dunes and other, with linear shape, related to earthen walls as evident from the presence of emerging remains. Two regions of interest related to wall S have been investigated (Fig. 3b). One (ROI1) refers to a sector of the wall (width ranging from 4 to 5.7 m, height from 20 cm to 6 m) that is well visible from both optical and radar data (Fig. 4). The second (ROI2) refers to an area including emerging walls (width ranging from 3.3 to 4.9 m, height from 0 to 5.8 m), microrelief and expected buried structures (Fig. 5).

ROI1 test site (Fig. 4) was selected to observe and discuss the backscattering behaviour in relation with the geometry of the wall, suitably 3D modeled by processing the aerial images taken from UAV, by using SfM method (as explained in section 3.3).
What strikes the eye is the different backscattering behaviour along the wall, as evident by the inhomogeneous range of greys. Brighter is the pixel tone, stronger is the reflector. The comparison between the SAR scene with the wall geometry put in evidence a greater reflectance energy (so, brighter grey tone!) in presence of normal reflections. The reflectance energy tends to decrease in presence of double bounce effect, and consequently the pixel tone tends to darken.

In the SAR picture in Fig. 4 (lower), pixels oriented linearly and parallel to the wall are characterized by black tone due to radar shadows (indicated with “sh” in Fig. 4) that occur on the ground areas that are not illuminated by the radar signal.

The above said considerations confirm the complexity of the interpretation of the backscattering behavior in presence of emerging structures. In the case under investigation, this complexity is mainly due to the irregular morphology of the wall, as common for earthen structures which are strongly affected by weathering (mainly wind erosion), and the presence of collapsed building materials scattered on the ground (adobe bricks and fragments).

Fig. 5 refers to ROI2. The image shows the results obtained from the elaboration of optical (5a) and SAR (5b) satellite data, and aerial images taken from UAV and processed by using SFM technique. Fig. 5a shows the Pleiades map, available at 0.50 m of spatial resolution for the test site under investigation with overlapped contours (in red and yellow) obtained from the integration of a topographical survey with the DEM derived by UAV-based survey.

Fig. 5a shows what is evident on ground, namely the surface earthen wall, indicated by white arrows and letters w1, w2 and w3. Fig. 5b shows the COSMO-SkyMed amplitude map with brighter pixels related both to emerging walls (the same visible from Pleiades scene), and to microrelief (indicated by m1) related to shallow walls.

In this case, the added value of SAR is clearly evident, although its resolution is lower respect to Pleiades image (3 m against 0.50 m). The presence of microrelief induces spatial changes in the roughness of the area that are detected by radar but completely invisible from the optical satellite image. In fact, the amplitude of the SAR signal is strongly affected by the presence of microrelief linked to the adobe remains and scattered material (as shown for ROI1, see Fig. 4) even if the latter are similar to the soil of the neighbouring areas. Their different roughness and compactness is able to produce a significant signal that can be detected by Cosmo SkyMed data. The microrelief m1 is very well visible from the very detailed DEM derived from UAV-based survey (see profile x-x’ in Fig. 5c).

The most relevant results of our investigation is in the fact that only one SAR image at a 3-m spatial resolution has been analyzed. It is important to highlight that the visibility of the remains is also due to the satellite parameters in terms of frequency, polarization and acquisition geometry.

At Southwest of ROI2 and wall w1, no backscattering behavior of potential archaeological interest is visible from the COSMO-SkyMed data, though the profile y-y’ on the DEM reveals the presence of a microrelief, whose topographical variation is less accentuated than the microrelief m1 (Fig. 5b).

However, it is reasonable to think that the wall continues towards Southwest.

In order to ascertain this hypothesis, at west of wall w1 (Fig. 6a), some geomagnetic investigations have been performed. Fig. 6b shows the resulted kriging magnetic maps which reveal some magnetic anomalies characterized by linear morphology. In particular, some anomalies are clearly referable to a buried wall aligned with the emerging wall w1 (Figs. 5a and 6b) and the microrelief m1 observed by SAR (Fig. 5b). The magnetic map (Fig. 6b) puts also in evidence further linear anomalies (indicated with yellow arrows in Fig. 6b), N-S and E-W oriented, probably due to the presence of buried remains. Unfortunately, the extension of magnetic map does not allow to say more about it.

The improved spatial characterization obtained by geomagnetic investigations is “in primis” due to the higher spatial resolution of magnetic maps so that it is possible to identify not only the prosecution of the wall ENE-WSW oriented, but also some other remains in the North – South direction.

From the archaeological point of view, it is not yet clear when these walls were built. The pottery materials observed during the field survey (conducted on December 2014, jointly with the archaeologists of the Museo de Sitio Pachacamac), suggest a dating between the Ychsma and Inca period. It is reasonable to think that the walls were built at a time when the two existing boundary walls (surrounding sectors I and II) were considered insufficient to control the entrance to the Ceremonial Center of Pachacamac from North [4].
5. Conclusions

The increasing availability of multi band SAR satellite systems with increasingly improved spatial resolution was caught by the archaeological community as an interesting opportunity to complement the information related to the presence of buried archaeological structures.

The question that arises is, how far this technology could represent an operational tool of knowledge, in order to guide the choices of archaeologists in the planning phase of the excavations?

To answer this question, increasing efforts are needed to assess the limits and potential of SAR, by appropriately selecting case studies, preferably investigated by using more geophysical and remote sensing technologies (see for example the experience by [26]), covering a large spectrum of archaeological features, characteristics of the soil and climatic and environmental conditions.

In this paper, a qualitative evaluation of the X-band COSMO SkyMed data capability in detecting archaeological features related to earthen buried remains is presented. This evaluation has been performed also using other remote sensing tools such as optical satellite data, geomagnetic prospections and high detailed topography, derived from the SM processing of aerial images taken from UAV.

The results obtained, on a test site including an adobe wall in the Northern area of Pachacamac, put in evidence the feasibility of X-band SAR data at high resolution, in particular, for the detection of microlief linked to the presence of earthen shallow remains.

A detailed 3D-geometry of the investigated wall, provided useful information on the radar backscattering behavior, in presence of emerging structures built in earthen material.

The test site showed that X-band radar data are not feasible for the detection of buried remains, which, in the test area, have been identified by geomagnetic prospections.

The experience described here is just a starting point for a more systematic validation activity of SAR in archaeology, through direct and/or remotely sensed data.

In the future, the integrated approach for the validation of SAR for archaeological purposes should be based on the use of:

- other geophysical techniques, such as GPR, in order to provide also information about the depth of archaeological deposits;
- remotely sensed data acquired at the same time to reduce any uncertainty related to possible changes of the geometry and shape of archaeological remains, especially in the case of raw earth structures, as well as the land cover characteristics.

Acknowledgements

The authors thank the Italian Ministry of Foreign Affairs for supporting the research activity of ITACA Missions in the framework of the project “Diagnostics for the Conservation, Archaeo-geophysics and risk assessment of cultural heritage in Peru (2014)”.

The COSMO-SkyMed data were provided by the Italian Space Agency under license agreement from ArcheoCosmo. Pleides imagery were provided by CNES.

Author contributions: Nicola Masini and Rosa Lasaponara conceived the entire application, performed SAR data processing and interpretation and wrote sections 1, 2, 1, 3.1, 4 and 5. Denise Pozzi Escot and Nicola Masini wrote section 2.2. Geomagnetic data have been acquired by Felice Perciante and Maria Sileo who wrote section 3.2. Geomagnetic data have been processed by Felice Perciante under the supervision of Enzo Rizzo who contributed to the writing of section 3.2. UAV aerial images have been acquired by Antonino Pecchi who processed the data and wrote section 3.2 under the supervision of Nicola Masini. Manuela Scavone contributed to the processing of aerial images and the writing of section 3.2.

References


Fig. 6. (a) Area investigated by geomagnetic techniques; (b) detail of magnetic map. Red arrows denote an anomaly related to a buried wall aligned along the emerging wall w1. Yellow arrows indicate other linear magnetic anomalies also referable buried structures.


