On the evaluation of Satellite COSMO capability in archaeological survey to detect earthen buried remains in desert areas: the case study of Pachacamac - Lima (Peru)

Journal:	*International Journal of Digital Earth*
Manuscript ID:	TJDE-2015-0109
Manuscript Type:	Original Research Paper
Keywords:	Cultural heritage, Earth Observation, Microwave remote sensing

On the evaluation of Satellite COSMO capability in archaeological survey to detect earthen buried remains in desert areas: the case study of Pachacamac - Lima (Peru)

Formatted: Font color: Black

Rosa Lasaponara[1], Nicola Masini[2], Antonio Pecci[2], Felice Perciante[1], Denise Pozzi Escot[3], Enzo Rizzo[1], Manuela Scavone[2], Maria Sileo[2]

[1] CNR-IMAA (Institute of Methodologies for Environmental Analysis), C.da Santa Loja, 85050, Tito Scalo (PZ), Italy.

[2] CNR-IBAM (Institute for Archaeological and Monumental Heritage), C.da Santa Loja, 85050, Tito Scalo (PZ), Italy;

[3] Museo de Sitio Pachacamac, Antigua Panamericana Sur Km. 31.5, Lurín,Lima, Perú

Abstract 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 located in a poorly investigated area 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 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 of earthen buried structures.

Keywords: satellite radar, COSMO, UAV, Pachacamac, earthen buried structures

Formatted: Font color: Black

Formatted: Font color: Black, English (U.S.)

Formatted: Font color: Black

Formatted: Font color: Black

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 at diverse scales of interest, moving from small artifacts to landscape level. 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 (i) by their inability to penetrate soil and (ii) by the absence of typical archaeological crop marks. Even if today a huge amount of SAR data are available, their potentiality and use are still underexploited in the archaeological operative practice.

In this paper we focus our attention on the joint use of satellite X-band radar data, aerial photographs captured from UAVs and magnetic prospection for detecting adobe remains in desert areas of Pachacamac-, one of the biggest archaeological sites of Peru, located at 31 South East of Lima, in the Valley of the Lurín River (see Figure 1).

Formatted: Font color: Black, Not Highlight

Formatted: Font color: Black

For more than 2,000 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 culture, (Shimada 1991). Thus, through the ages Pachacamac also became a center of the cultural and economic life of the Andean world surviving from one civilization to another and also thriving, expanding and facing numerous socioeconomic issues.

To enrich the amount of information in Pachacamac, we conducted our investigations in a non-invasive, non-destructive way, using the most powerful digital tools nowadays available for archaeology: satellite radar, aerial photographs and magnetic prospection. The availability of active and passive sub-metric remote sensing data provides challenging opportunities to improve the extraction of information, from the qualitative and quantitative point of view, also in the case of subtle signals which typically characterize buried and shallow archaeological remains.

The identification of these structures depends on the contrast between the geophysical proprieties of the archaeological deposits and its surrounding. For example, wells, tombs, stone masonry, walls, ditches can be identified more easily than earthen remains which tend to exhibit very low physical contrast respect the surrounding soil (Masini & Lasaponara 2009; Bonomo et al. 2013) having a similar material composition.

The test site of our investigation is an area located at North of the archaeological site of Pachacamac, including very thick walls built in adobe (see Figure 2). It is part of an ancient city wall, which probably enclosed a residential area and cemeteries, dating back to a period ranging from Ychma to Inca ages.

Formatted: Font color: Black

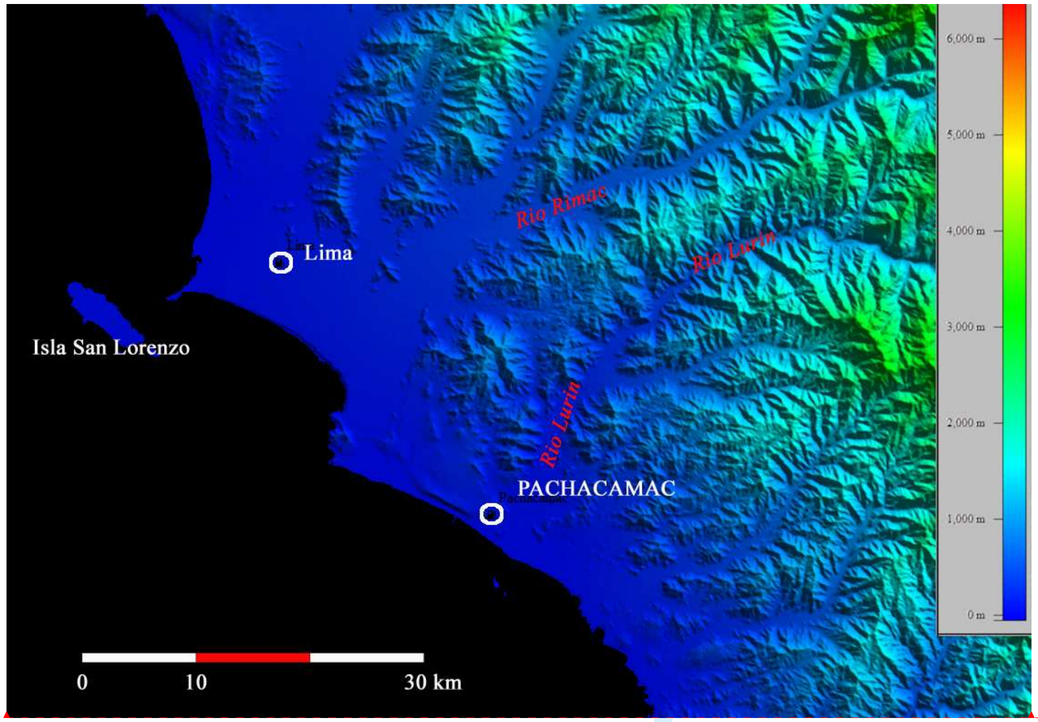
With such regard, it is reasonable to believe that a larger part of the wall is under the current ground level, the rest is shallow or emerging. The paper shows the results of a multiscale and multisensor approach, including satellite optical and SAR remote sensing, geomagnetic prospection and UAV, aimed at detecting buried and shallow remains referable to the ancient earthen walls.

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

2.1 - Brief historical overview

Formatted: Font color: Black

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 (see Figure 1). The site covers a total area of around 465 hectares, among which the third is occupied by monuments such as temples, pyramids with ramp and palaces.



Formatted: Font color: Black

Formatted: Font color: Black

Figure 1 - Location of Pachacamac

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 2th 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 (200 BC-600 AD). Under Huari (550-1100 AD) Pachacamac reached its apogee. The sanctuary area became a city used as administrative center of great importance throughout the Andes. The Huari influence can be seen in ceramic objects, paintings and architecture ("Painted Temple", see 4 in Figure 2).

The Ychma (1100-1470) civilization followed after the collapse of the Huari. During the Ychma period Pachacamac continued its expansion becoming a city-state and, later, the capital (known as Ychsma), 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", 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, the city, renamed Pachacamac, became an important ceremonial and administrative center. The Incas maintained the sanctity of the place and allowed the priests of Pachacamac to continue to profess their religion and their rites. They built the Temple of the Sun, and the palaces of Acllahuasi, - 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 3.2). In the same period, further settlements (see sectors III and IV in Figure 2) including residential area and cemeteries were built at North of the archaeological area.

2.2 Archaeological Area

Formatted: Font color: Black

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 (Franco Jordan 1993a, 1993b) and cemetery, for an extension of 18.8 Ha (see 1, 4 and 5 in Figure 2, respectively). The second wall, defining sector II, contains roads, cemeteries, many squares and courts, pyramidal monuments, known as pyramid with ramp (Eeckhout 1995; Paredes Botoni & Franco Jordan 1987), 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)

The Sector III, called "outer city", extended from the inner city (sectors I and II) to the outer city walls, for an extension of around 90 ha (see Figures 2 and 3). Herein the archaeologist Max Uhle, found vast residential areas and a cemetery.

Finally, the Sector IV is located at North of the 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 between the Sectors III and IV and includes a section of the walls which crosses the desert hill at North of the archaeological area, 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 4m. Along the direction of the wall (see red arrows in Figure 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 buried walls and other possible structures.

Formatted: Font color: Black, Not Highlight
Formatted: Font color: Black
Formatted: Font color: Black, Not Highlight
Formatted: Font color: Black

Figure 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 ones locate between sectors III and IV, the second ones are located at North East near the modern town of Pachacamac. The red box indicated the area object of investigation

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

To enrich the amount of information for the area of interest, we conducted our investigations in a non-invasive way, using the most powerful digital tools nowadays available for archaeology: radar and optical satellite data, aerial photographs taken from UAV and magnetic survey. 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, also in the case of subtle signals which typical characterize buried and shallow archaeological remains.

3.1. SAR Satellite remote sensing as tool for the detection of archaeological features

The use of satellite radar data in archaeological investigations can offer great potential for site detection, documentation and monitoring especially in desert areas where optical data generally are strongly limited by their inability to penetrate soil and by the absence of typical archaeological crop marks (Lasaponara & Masini 2013). Even if a huge amount of SAR data are available today, their potentiality and use are still underexploited in the archaeological operative practice. Satellite Synthetic Aperture Radar (SAR) has entered into a golden age with a rich availability of data from both historical archives and numerous operative satellite platforms, which, compared to the past, offer advanced imaging mode capability available at diverse (L,C and X) bands (Berger & Aschbacher 2012.).

Moreover, the currently available satellite SAR systems provide data with a greater flexibility in the selection of incidence angles and polarizations even in the scale of one meter and less. These advanced technical characteristics make the use of radar data very attractive for numerous application fields, including archaeology. Nevertheless, a correct identification and interpretation of archaeological features (marks) on the basis 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 sensed surface. Actually, from the historical points of view one of the main important applications of SAR data for archaeology and palaeoenvironmental studies has been focused on the exploitation of SAR penetration capability particularly significant in drought desert areas (McCauley et al. 1982; El-Baz F. 1998). Only recently SAR data, in particular X-band one at high resolution, have been using for the reconnaissance of archaeological microrelief (Chen et al. 2015).

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 mainly, for example 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 in generally beneficial for the archaeological feature extraction, but the use of filtering to reduce noise could also filter out the target.

For the purpose of our analysis to cope with this issue, after the partial noise removal using Enhanced Lee (Lee Jong-Sen 1980; Lopes et al. 1990), we also include textural and morphological filter (Rama Bai 2010). 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 (Peters 1995) 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.

In Pachacamac, at North of the fenced archaeological area (see figure 3a) we used a COSMO-SkyMed data acquired on 02 January 2012 with Strip Map mode, at 4 m geometric resolution (for additional details on the data see captions of Figure 3). The visual comparison of the satellite radar data (Figure 3a) with optical satellite data (Figure 3b) puts in evidence a greater number of features visible from radar data.

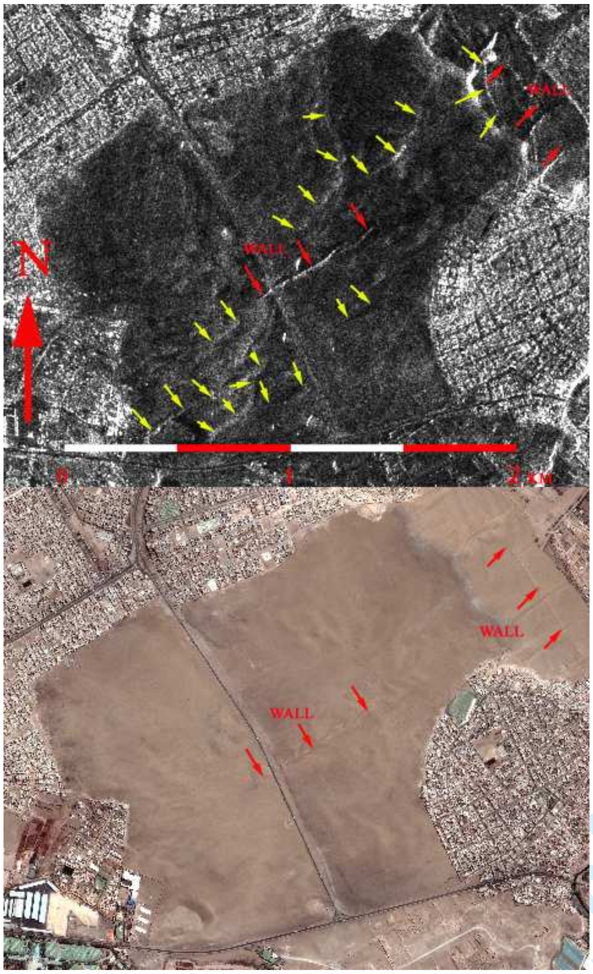


Figure 3 – COSMO-SkyMed (up) radar and Pleiades (bottom) of the study area. Red arrows indicate the emerging hearten wall, whereas yellow arrows denoted the anomalies detected by radar data. TheCOSMO-SkyMed is acquired on 02 January 2012 with Strip Map mode, along the descending orbit, right look side, with VV polarization, at 4 m geometric resolution (see Figure). The data is a Geocoded product (1C level) obtained projecting the SLC (Single-look Complex) product (which in its turn a raw data focused in slant range-azimuth projection) onto a regular grid in a cartographic reference system whose surface is the earth ellipsoid.

3.2. Geomagnetic method

Formatted: Font color: Black

The magnetic survey is one of the most important non-destructive investigation techniques widely used in archaeological prospection. It is based on the measurement of small local variations of the earth's magnetic field due to the presence of buried object (i.e. man made buried structures) . The geomagnetic approach allowed us the possibility to obtain 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 were performed using an optical pumping magnetometer G-858 (by Geometrics) in gradiometric configuration, with two magnetic probes set in a vertical direction (1m each other). This configuration removes the diurnal variations of the natural magnetic field. Among the various acquisition modalities provided by the magnetic sensors, the magnetic measurements were 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 (figure 6) was obtained by several parallel profile obtaining a regular grid with an interspaced line of 1m and a sampling rate of 10Hz, obtaining more than 4000 gradiometric data for an investigated area of about 50 x 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 (Rizzo et al, 2010). A wide range of processes were provided, allowing the data to be manipulated to produce the best possible interpretation. The rough magnetic data were filtered to obtain the best S/N ratio providing some processes: the pass-band filter, to remove high or low frequency components in the survey; the despike tool by scans the composite using a uniform weighted window looking for datapoints that exceed the mean of the window and are replaced by either the mean; stretch compensation for errors due to inconstant operator walking, zig-zag effect and destripe to remove the striping effect between grids caused by directional effects. In order to highlight the main geomagnetic linear anomalies, the data were further processed using a Kringing interpolator with a linear variogram (Rizzo et al., 2005; Rizzo et al., 2010). The figure 6 shows the kriging interpolated magnetic map where several linear anomalies are visible. The large EW linear anomalies (red arrows) is clearly in continuum with the main visible wall structures. Moreover, several parallel and orthogonal lines seems to detect more buried structure close the main walls.

Formatted: Font color: Black

3.3 Aerial data UAV system, image acquisition and processing

Formatted: Font color: Black

Undoubtedly, compared to traditional aerial archaeological, the UAVs offer several advantages, particularly low cost and ability to cover large in a short window of 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 Nex

& Remondino (2013). A typical UAV platform for geomatics purposes have costs ranging from 1,000 to 50,000 Euro, depending on (i) payload, (ii) instrumentation, (iii) degree of automation (iii) autonomy in terms of battery. Low-cost solutions generally offer lower payload and usually require human assistance in the take-off and landing phases (see for example Neitzel and Klonowski 2011). For the purpose of our investigation we adopted a low cost drone Dji Phantom Vision 2 plus, a radio-controlled quadcopter, able to take off and land vertically on any surface. It has a structure in carbon fiber with a weight of 1242 grams, a diameter of 350 millimeters and a payload of about 500 grams. 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.

Formatted: Font color: Black

UAV surveys, performed in sectors III and IV of Pachacamac, aimed at providing : 1) the DEM of the area in order to observe and interpret further microrelief linked to shallow remains; 2) a very detailed model of the walls enabling us to analyze building techniques and decay patterns of adobes.

For the first aim images were acquired in automatic and zenith mode at 30 m height. For the second one the images were captured in manual, oblique and nadiral mode, at a height from 8 to 20 m.

Data processing of aerial photographs aimed at providing 3d e geometry from 2D 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 (Agisoft PhotoScan User Manual, 2014). The processing includes the following steps: i) the selection and loading of photos, captured with correct overlap requirement (60% of side overlap + 80% of forward overlap) aimed at minimizing blind-zones; ii) computation of camera position and orientation for each photo, alignment of photos and building of a sparse point cloud; iii) generation of dense point cloud model which allows to calculate depth information for each camera position, iv) building 3d model polygonal mesh ; v) and, finally, building model texture.

4 Results and Discussion

The full exploitation of data provided by the diverse sensors (from aerial, space and ground acquisition) herein used were fruitfully integrated within a GIS environment which provided effective solutions for the management, integration and interpretation of heterogeneous data sources. In this section we will discuss results obtained from each technology one by one.

Figures 4 show the results obtained from the elaboration of optical (4a) and SAR (4b) satellite data. In details, Figure 4a shows the Pleiades map, available at 0.6 m of spatial resolution, for the test site under investigation with overlapped the contours (in red and yellow) obtained from a topographical survey. Figure 4a shows what is evident on ground namely the surface earthen wall built for defensive purpose. Figure 4b shows the COSMO-SkyMed amplitude map with brighter pixels related both to emerging walls, (indicated by white arrows, and to microrelief related to shallow walls, indicated by the red box and arrows (denoted also by w1). The added value of SAR is evident although its lower resolution respect to Pleiades (4 m against 0.60 m). The presence of microrelief induces spatial changes in the roughness of the area that is easily detected by radar but completely invisible to the optical satellite image. In fact, the amplitude of the SAR signal is strongly affected by the presence of adobe remains even if the constituent material of them are similar to the neighbouring areas but the different roughness and compactness is able to produce a significant signal that can be detected by the SAR..

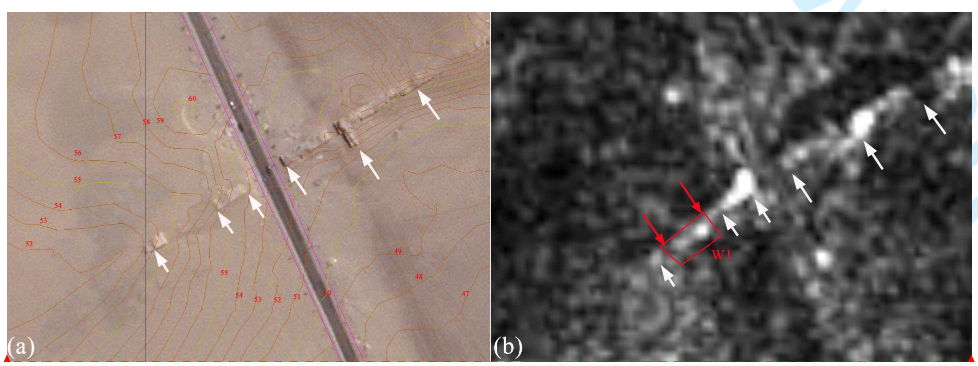


Figure 4 Results obtained from the elaboration of optical Pleiades (4a) and SAR (4b) satellite data

Formatted: Font color: Black
Formatted: Font color: Black
Formatted: Font color: Black

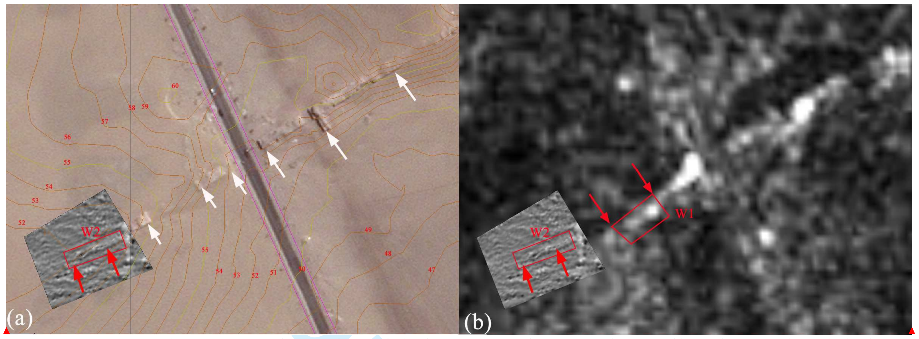
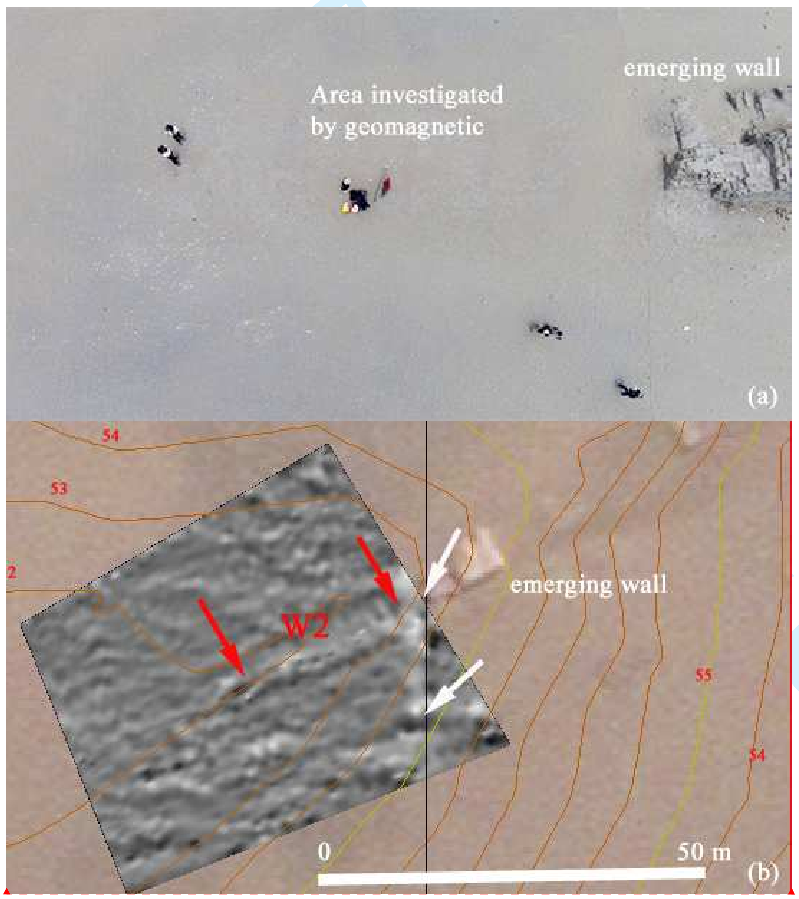


Figure 5 Magnetic map overlapped to Pleiades (5a) and SAR (5b) satellite data and aerial photographs

Formatted: Font color: Black

Formatted: Font color: Black



Formatted: Font color: Black

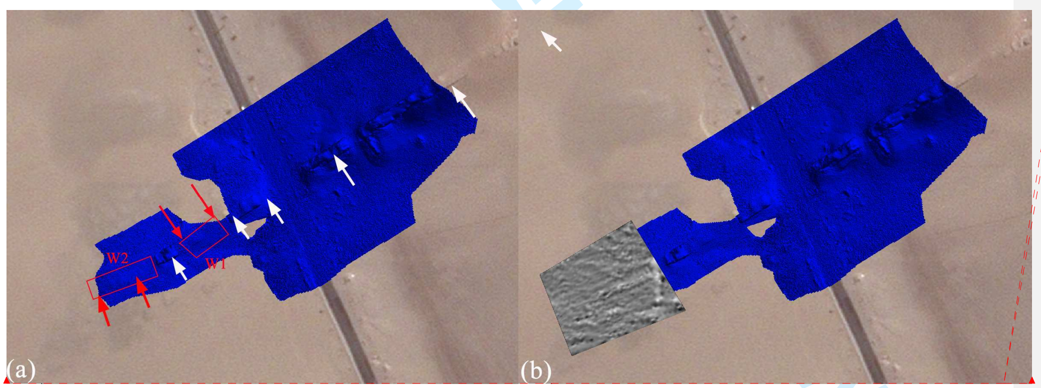
Formatted: Font color: Black

Figure 6 - (a) Area investigated by geomagnetic techniques; (b) Detail of magnetic map. Red arrows denote an anomaly related to a buried wall (w2) aligned along the emerging wall (Figure 4a; 8lower); white arrows indicate another linear magnetic anomaly also referable to a buried structure.

The most important and relevant results of our investigation is in the fact that we analyzed only one SAR image at a 4 m spatial resolution. It is important to highlight that the visibility of the remains is also due to the satellite parameters in terms of frequency, polarization, acquisition geometry (ascending/descending). From the archaeological point of view, it is not yet clear when the walls were built. The materials collected during our field survey at the surface suggest a dating between the end of the Ychma period and the 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 no longer considered sufficient to control the entrance to the Ceremonial Center of Pachacamac from North. At the same time the new walls were a good protection of residential areas that were built north of the sacred area.

Formatted: Font color: Black, Spanish (Peru)

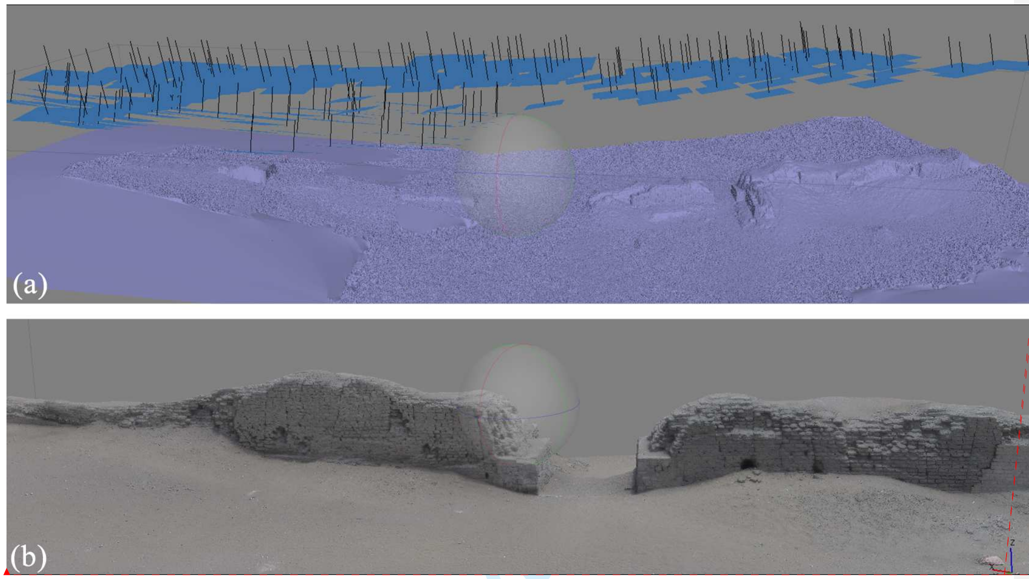
Formatted: Font color: Black



Formatted: Font color: Black

Formatted: Font color: Black

Figure 7 Aerial photographs, taken at the same time as the magnetic survey, overlapped to Pleiades map (6a) and Magnetic map overlapped both to Aerial photographs and Pleiades map



Formatted: Font color: Black

Formatted: Font color: Black

Figure 8 - Results from the SfM based processing of aerial images captured from drone. (a) Mesh of 3d model of adobe wall : (b) detail of textured 3d model

Results obtained from the magnetic maps add further information on the presence of walls in the subsoil. Figures 5a and 5b show the magnetic maps overlapped to Pleiades and COSMO-SkyMed data, respectively. A zoom of magnetic map is provided in Figure 6. The anomalies herein observed are clearly referable to a buried wall (see w2 in Figures 5-6) aligned with the emerging wall and the microrelief (w1) observed by SAR.

The zoom of the magnetic map (see Figure 6) puts also in evidence another linear anomaly, N-S oriented, probably due to the presence a buried structure. 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 is possible to identify not only the prosecution of the wall ENE-OSO oriented, but also some other remains in the North –South direction which are less visible from SAR being vertical to the acquisition geometry.

Finally drone survey enabled us to enrich the data set providing detailed 3D model and capturing the emerging remains acquiring data with diverse spatial resolutions (i) at coarse scale that provides the possibility to have a detailed DTM of the area at a landscape level and (ii) detailed scale which enable us to obtain very detailed information on the wall and in turn the possibility to better investigate the built technique. Moreover, the DTM allows us to spatially characterize with a very high detail the microrelief w1 detected by using SAR.

5 Final remarks

Formatted: Font color: Black

In this paper for the first time the results of the evaluation of the detectability of buried earthen remains using satellite SAR technology have been presented. The results we obtained, on a test site in the Northern area of Pachacamac, put in evidence the feasibility of SAR data sing other investigation methods such as geomagnetic and surveys by using UAV for archaeological purposes. The adopted multisensor and multiscale approach helped in the improvement of the archaeological interpretation of radar signals in presence of buried, shallow and emerging walls built in adobe. The results from our investigations clearly pointed out that digital data source from aerial, satellite and ground platform we used for the current investigation integrated with geophysical prospection and other documentary sources can suitable support study, documentation, management and systematic monitoring activities for archaeological and historical landscape. Landscape is an integral part of our archaeological heritage being that it preserves the main features that identity and exhibit the evolutionary history of civilization over time. The analysis and interpretation of these features have a strategic importance for the promotion and preservation of the archaeological landscape, which today, unfortunately, is more and more exposed to degradation phenomena. The identification of traces of past human activities, still fossilized in the modern landscape, is the first important step to preserve these “proof” of the landscape history from “extinction processes”.

Cultural heritage management and preservation is a strategic priority to assure cultural treasure and evidences of the human past to future generations but, at the same time, it also represents a strategic and valuable economic asset, if inspired to sustainable development strategies. This is an extremely important key factor for countries, as Peru, which are owners of an extraordinary cultural legacy, that is today particular fragile due to many reasons including industrial risk, pollution impacts, urban sprawl as in the current case and degradation factors. Considering the potential adverse impact of numerous threats to cultural heritage and landscape it is important to ensure the preservation and enjoyment of legacy as unique resources (non -renewable) to be protected not only for the future generations but also for a sustainable economic exploitation coupled with social and cultural developments.

Formatted: Font color: Black

Acknowledgments

This research was performed in the framework of the projects : (i) ‘Earth Observation technologies for the survey, the study and the valorization of ancient hydraulic systems “ jointly funded by the Italian CNR and Peruvian CONCYTEC leaded by Rosa Lasaponara and (ii) ITACA Archaeological mission funded by the Italian Ministry of Foreign Affairs Mission and International Cooperation leaded by Nicola Masini. COSMO-SkyMed data were provided by the Italian Space Agency, under licence agreement Archeocosmo. Pleiades data were provided by Centre national d'études spatiales (CNES). With such latter regard, in particular we thank Alain Gleyzes and Claire Tinel of CNES. Moreover we thank Jorge Antonio Abad Flores of Pachacamac Museum for topographical measurements, the archaeologist Janet Liliana Oshiro Rivero of Pachacamac Museum for her important support during field surveys, Gabriele Bitelli and Emanuele Mandanici of University of Bologna for the orthorectification of the Pleiades image.

Author Contributions

Rosa Lasaponara and Nicola Masini processed and analyzed the optical and SAR satellite data, carried out the integration and interpretation of satellite, aerial and geomagnetic data set and wrote the whole paper (except section 4.2). Antonio Pecci acquired the aerial photographs by drone and elaborated the data with the contribution of Scavone. Felice Perciante and Maria Sileo acquired the data by geomagnetic tool. Enzo Rizzo elaborated the geomagnetic data and wrote section 4.2 with Felice Perciante . Denise Pozzi-Escot provided information on the study area and contributed to the interpretation of results.

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Reference

Agisoft PhotoScan User Manual (2014): Professional Edition, Version 1.1

Berger M., Aschbacher J., Preface: The Sentinel missions-new opportunities for Science. Remote Sensing of Environment, 120 (2012), 1-2

Bonomo N. , Osella A., Ratto N., GPR investigations at an Inca-Spanish site in Argentina, Near Surface Geophysics, Vol 11, No 4, August 2013 pp. 449 - 456, DOI: 10.3997/1873-0604.2013021

Chen F., Masini N., Yang R., Milillo P., Feng D., Lasaponara R., A Space View of Radar Archaeological Marks: First Applications of COSMO-SkyMed X-Band Data, Remote Sensing 7 (2015) 24-50.

Eeckhout P. 1995. Pirámide con rampa No III de Pachacamac, costa central del Perú: resultados preliminares de la primera temporada de excavaciones (zona 1 y 2). En: Bulletin de l'Institut Français d'Etudes Andines, Tome 24, No 1, 169-214. Instituto Francés de Estudios Andinos, Lima.

Eeckhout P. 2004. Pachacamac y el Proyecto Ychsma (1999 - 2003). EnBoletín del Instituto Francés de Estudios Andinos nº 33(3). IFEA, pp. 425-448.

El-Baz F. 1998, 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

Eder-Hinterleitner, A.; Neubauer, W.; Melichar, P. Restoring magnetic anomalies. Archaeological Prospection 1996, 3, 185–197

Franco Jordan R. 1993a. El Centro Ceremonial de Pachacamac: Nuevas Evidencias en el Templo Viejo. Boletín de Lima No. 86, pp. 45-62. Lima-Perú

Franco Jordan R. 1993b. Los dos Templos Principales de Pachacamac, Breve Síntesis". En Revista del Museo de Arqueología No. 4. Universidad Nacional de Trujillo. pp.55-78. Perú

Goodman, D. GPR Slice v 7.0 Manual. From http://www.gpr-survey.com June, 2013.

Lasaponara R., Masini N. 2013, Satellite Synthetic Aperture Radar in Archaeology and Cultural Landscape: An Overview. Archaeological Prospection, 20, 71-78, doi: 10.1002/arp.1452

Lee Jong-Sen 1980. Digital Image Enhancement and Noise Filtering by Use of Local Statistics. IEEE Transactions on Pattern Analysis and Machine Intelligence 1980, 2, 165-168.

Lopes, A., Touzi, R.; Nezry, E. 1990. Adaptive Speckle Filters and Scene Heterogeneity. IEEE Transactions on Geoscience and Remote Sensing, 28(6), 992-1000.

Masini N., Lasaponara N., Orefici G. 2009, Addressing the challenge of detecting archaeological adobe structures in Southern Peru using QuickBird imagery, Journal of Cultural Heritage, 10S, pp. e3–e9.

McCauley J.F., Schaber G.G., Breed C.S., Grolier M.J., Haynes C.V., Issawi B., Elachi C., Blom R. 1982. Subsurface valleys and geoarchaeology of the eastern Sahara revealed by shuttle radar, Science 218, 1004-1020

Neitzel F. and Klonowski J. 2011. MOBILE 3D MAPPING WITH A LOW-COST UAV SYSTEM. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XXXVIII-1/C22, 39-44, Volume XXXVIII-1/C22

Nex, F. and Remondino, F. 2013. UAV for 3D Mapping Applications: A Review. Applied Geomatics, 6, 1-15.

Paredes Botoni P. y Franco Jordan R. 1987 Pachacamac. Las Pirámides con Rampa: Cronología y Función. En "Gaceta Arqueológica Andina", No 13: INDEA - Lima.

Peters, R.A. A New Algorithm for Image Noise Reduction Using Mathematical Morphology. IEEE Transaction on Image processing 1995, 4(5), 554-567

Field Code Changed
Field Code Changed
Field Code Changed
Field Code Changed
Field Code Changed
Field Code Changed
Formatted: Font color: Black
Formatted: Italian (Italy)
Formatted: Font color: Black
Field Code Changed
Field Code Changed
Formatted: Font color: Black

Rama Bai, M. A 2010. New Approach For Border Extraction Using Morphological Methods. International Journal of Engineering Science and Technology, 2(8), 3832-3837

Rizzo E., D. Chianese and V. Lapenna (2005). Integration of magnetometric, gpr and geoelectric measurements applied to the archaeological site of Viggiano (Southern Italy, Agri Valley-Basilicata). Near Surface Geophysics, 3,13-19.

Rizzo Enzo, Nicola Masini, Rosa Lasaponara, Giuseppe Orefici (2010). ArchaeoGeophysical methods in the Templo del Escalonado (Cahuachi, Nasca, Perù). Near Surface Geophysics Vol 8, No. 5, October 2010, pp. 433-439 doi: 10.3997/1873-0604.2010030

Scollar, I.; Tabbagh, A.; Hesse, A.; Herzog, I. Archaeological Prospecting and Remote Sensing; Cambridge University Press, Cambridge, 1990.

Shimada I., 1991 Pachacamac Archaeology. Retrospect and Prospect, en Pachacamac. A Reprint of the 1903 Edition by Max Ühle. Philadephia: University of Pennsylvania Press.

Formatted: English (U.S.)