Investigating Natural Hazards in the Peruvian Region of Nasca with Space-Borne Radar Sensors

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Abstract

ENVISAT ASAR IS2 C-band imagery from the European Space Agency (ESA) archive was processed over the Peruvian region of Nasca, to investigate landscape modifications and dynamics of natural hazards and surface processes. Changes of radar backscattering (σ^0) were computed for the period 2003–2007, and the temporal evolution of the Rio Grande drainage basin was assessed. ASAR amplitude information rather than coherence and phase, was exploited to monitor environmental changes that may cause detrimental effects on natural and cultural heritage. The comparison of multi-platform satellite imagery allowed the detection of aqueduct systems (the so-called '*puquios*') designed by ancient Paracas and Nasca Civilizations (fourth century BC to sixth century AD) for water collection and supply.

Keywords

Land surface processes • Synthetic Aperture Radar • Change detection • Cultural heritage • Nasca

Synthetic Aperture Radar on Nasca Heritage

The Peruvian region of Nasca is widely renowned for the millennial archaeological features—the UNESCO WHL Lines and Geoglyphs of Nasca and Pampas de Jumana, the World's largest adobe Ceremonial Centre of Cahuachi and the ancient aqueduct systems of *puquios*—which testify a long history of human occupation since 2,000 BC along the tributaries of Rio Grande, i.e. Rio Ingenio, Rio Nazca and Rio Taruga.

Cultural heritage and landscape of Nasca are chronically exposed to natural hazards, mainly flash floods and run-off of sandy materials from unstable slopes. Archaeological evidences testify that the decline of Cahuachi, in the fourth phase of its history (AD 350–400), was due to a series of mudslides and severe earthquake (Masini et al. 2012, and references therein).

To investigate the impact of natural hazards of the heritage and landscape of the region, we implement change detection analysis based on exploitation of satellite Synthetic Aperture Radar (SAR) archives. This research also

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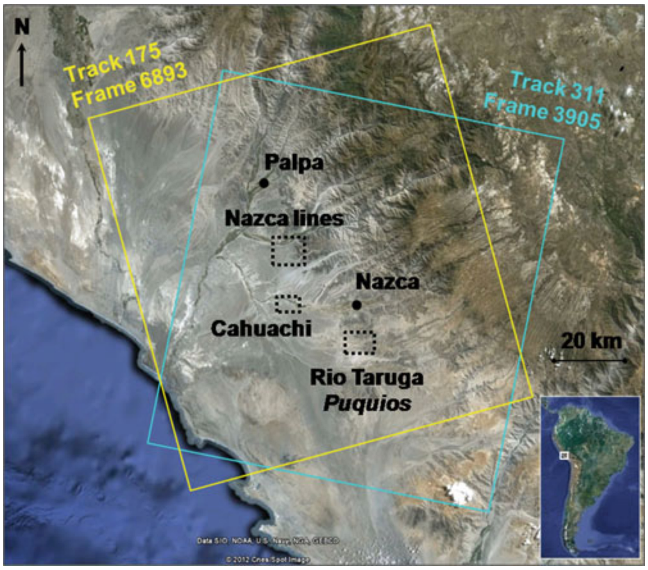

Fig. 1 Areas of interest and ENVISAT ASAR IS2 footprints in ascending and descending mode over the Nasca region, Peru (Google earth © 2012 Cnes/Spot Image) (modified from Cigna et al. 2013)

complements the activities of the Italian mission of heritage Conservation and Archaeogeophysics (ITACA), which involves researchers from the National Research Council (CNR) of Italy. Differently from previous studies that used interferometric coherence (Lefort et al. 2004; Ruescas et al. 2009) and its spatial variation on the micro- and meso-relief scale (Baade and Schmullius 2010), our paper presents the results obtained by making the best out of amplitude information contained within SAR imagery.

Input Data and Methodology

The input data that we used for our study cover the whole natural and cultural landscape of the Nasca region in Southern Peru (Fig. 1) and include:

– 8 ENVISAT ASAR IS2 scenes acquired in descending mode between 04/02/2003 and 15/11/2005;
– 5 ENVISAT ASAR IS2 scenes acquired in ascending mode between 24/07/2005 and 11/11/2007.

SAR-based results were also integrated and cross-validated with multispectral Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data acquired on 30/05/2003, 01/06/2004 and 10/06/2007 in the visible–near-infrared (VNIR), shortwave infrared (SWIR) and thermal infrared (TIR), with spatial resolutions of 15, 30 and 90 m respectively, and derived Normalized Difference Vegetation Index (NDVI) and Water Index (NDWI) maps.

We analysed and reconstructed the temporal evolution of radar signatures of the targets on the ground in the monitoring period 2003–2007. We followed the method of raw data focusing into Single Look Complex (SLC), absolute radiometric calibration and co-registration described in Cigna et al. (2013) and, finally, we retrieved the time series of radar backscattering coefficient (σ^0).

According to the coded radar terminology (cf. ESA, Radar Glossary 2013), this parameter corresponds with the normalized estimate of the radar return signal (σ) from a distributed target, and it is defined as per unit area on the ground.

For each image pixel i, the temporally averaged backscattering coefficient was obtained using the formula:

$$\overline{\sigma}_i^0 = \frac{1}{n}\sum_{t=t_1}^{t=t_n} \sigma_i^0(t) \quad (1)$$

where

– t_1 and t_n are the acquisition times of the first and last ASAR scenes of the stack, respectively;
– n is the total number of scenes of the stack;
– $\sigma^0{}_i(t)$ is the pixel backscattering coefficient at time t.

We also derived and geocoded the following products based on the two stacks of co-registered Multi Look Intensity (MLIs) images:

– *Time series of spatially averaged radar signatures for selected Areas Of Interest* (AOIs)—i.e. graphs showing temporal variation of the average σ^0 of the N pixels within each AOI;
– *Image ratios* ($R\sigma^0$) *of different pairs of spatially filtered MLIs*—which enhance σ^0 changes occurred over the scene during the time interval between two MLIs;
– *RGB* (Red-Green-Blue) *or RC* (Red-Cyan) *colour composites of 3 or 2 MLIs respectively*—where pixels with constant σ^0 are shown with grey levels, while those that changed are highlighted with colours of tint corresponding with the scenes recording higher σ^0.

Results and Discussion

Our study aimed to: (1) explore potentials for monitoring and rapid mapping of land surface processes; (2) create amplitude-based change detection maps to image landscape changes in areas of human occupation; (3) use SAR imagery to improve knowledge of ancient systems of water management.

Monitoring Landforms and Natural Hazards

Assessment of changes in the surface backscattering properties is an effective strategy to map fast land processes and scenes which are rapidly evolving. Mass movement

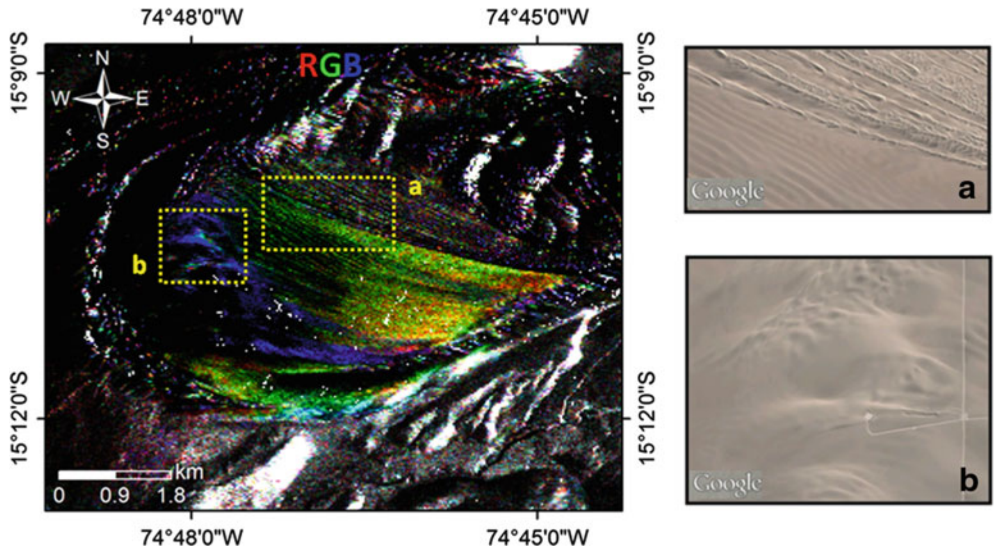

Fig. 2 RGB colour composite of a sand dune south of Cerro Blanco obtained by comparison of ASAR descending scenes acquired on 04/02/2003, 15/04/2003 and 24/06/2003 (*red*, *green* and *blue channels*, respectively). Google earth (© 2013 DigitalGlobe) views in (**a**) and (**b**) correspond with the areas within the *yellow dashed boxes* (modified from Cigna et al. 2013)

phenomena such as earth/debris flows and sand dune displacements significantly alter the terrain morphology and, consequently, its response to the microwave radiation. Whatever is the event that affected the monitored area, the latter still continues backscattering the incident radiation and σ^0 changes can be estimated over time. Whereas, for instance, the destruction and disappearance of radar targets with stable dielectric properties due to severe natural events and/or human-induced intentional or occasional damages, prevent any Persistent Scatterer Interferometry (PSI) analysis to be performed successfully [see the specific comments reported in Tapete et al. (2012, 2013a) with regard to the impacts on SAR-based archaeological applications].

In arid regions, wind-driven dynamics of sand dune displacements and mass movements triggered by sudden rainfall events are hazards of high relevance. Impacts on cultural features are quite frequent, especially when scatterers and structures are spread over wide regions, which are difficult to monitor periodically.

We tested our approach to investigate surface evolution of a sand dune area located about 30 km south of Cerro Blanco (a mountain considered sacred by the inhabitants of Cahuachi). Figure 2 shows the RGB colour composite of MLIs acquired on 04/02/2003, 15/04/2003 and 24/06/2003. The green-yellow coloured portion is related to an increased reflectivity in February and April 2003. This result clearly suggests the occurrence of movements of sand material, mostly occurred between April and June, which significantly modified the local surface morphology/orientation, and the related radar backscattering.

Comparison with Google earth clarifies the nature of the processes affecting the sand dune surface (Fig. 2a, b).

Amplitude-Based Environmental Assessment

Multi-temporal change detection, complemented with ASTER-based NDVI and NDWI estimates, allows regional-scale zoning of areas affected by σ^0 changes due to seasonal/yearly fluctuations of water availability. This assessment is highly helpful especially over fluvial areas and riverbeds, where long-standing human activity has significantly modified the land use.

A couple of ENVISAR ASAR scenes acquired during the same month of two consecutive years (November 2004 and 2005) were compared to detect yearly changes, and change detection maps were produced (Fig. 3). Orange-red coloured areas over agricultural fields indicate a slightly decreased backscattering from 2004 to 2005, while three localized areas in blue show an increase of σ^0 up to 4–5 times the initial values (Fig. 3). The examination of the ASTER images acquired in June 2003 and 2004 indeed highlights a general decrease in the reflectance in the NIR band and the vegetation cover over the eastern part of this area (Fig. 4), even where increased backscattering is found.

Detection of Ancient Water Systems

Discrimination of σ^0 properties over the monitored scene can lead to the recognition of morphological features attributable to archaeological remains and traces of past human occupation. Besides geometry and surface roughness, soil moisture content and material composition have also an effect on the surface brightness in the radar images.

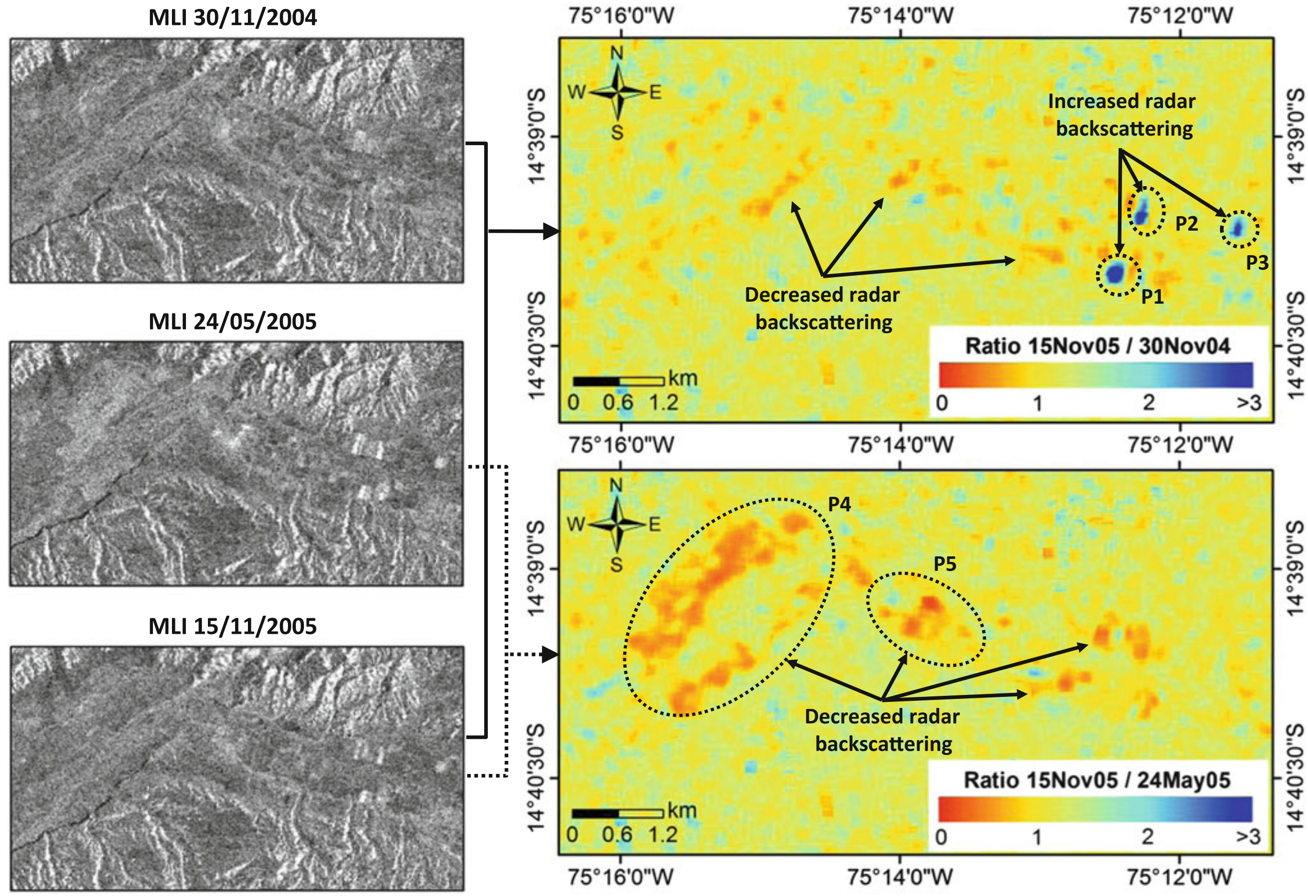

Fig. 3 Amplitude change detection maps obtained over the Rio Ingenio floodplain by ratioing the backscattering coefficient ($R\sigma^0$) estimated in November 2004 and November 2005 (yearly basis), and May 2005 and November 2005 (intra-year assessment) respectively (modified from Cigna et al. 2013)

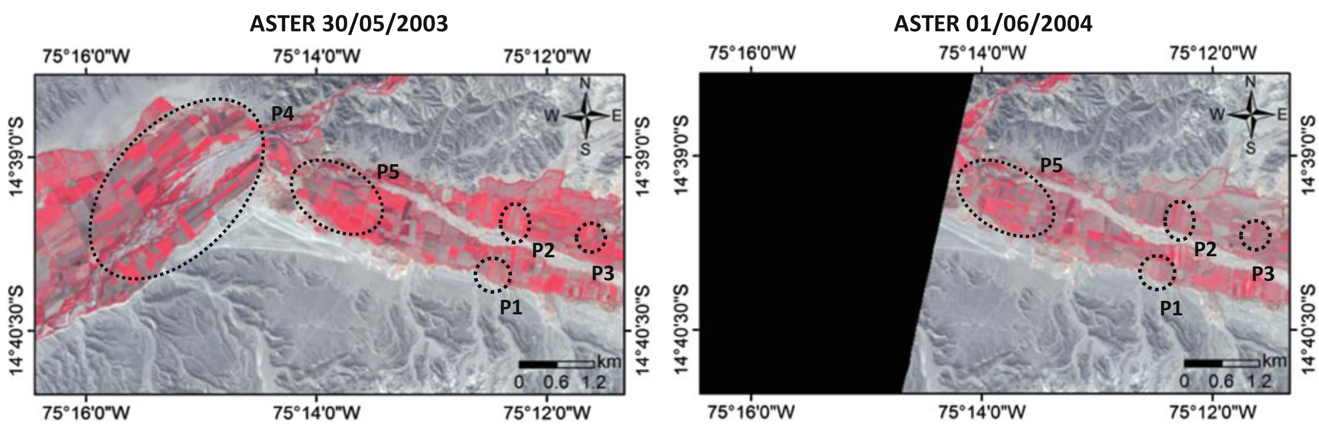

Fig. 4 ASTER 2003 and 2004 RGB composite of bands 3N-2-1 covering the same portion of the Rio Ingenio floodplain shown in Fig. 3 were used to correlate backscattering coefficient changes with vegetation variations over a similar temporal period. The areas P1-P5 correspond with those affected by $R\sigma^0$ changes (compare with Fig. 3; modified from Cigna et al. 2013)

This aspect was used in this study to distinguish still functioning *puquios*—an ingenious system of water collection and storage through subterranean galleries built by the Nasca Civilization—and those currently abandoned. RC colour composites of two MLIs acquired on 30/11/2004 and 15/11/2005 and ASTER-derived 2003–2004–2007 NDVI and NDWI suggest changes of soil moisture and vegetation over a large dry hydrographic reticulum lying

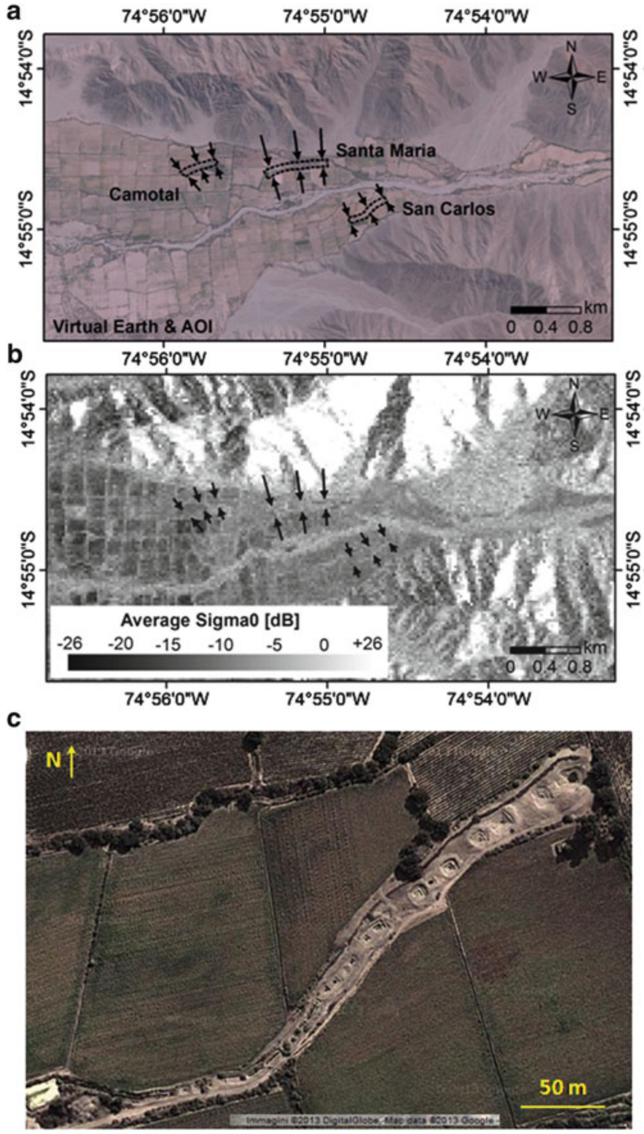

Fig. 5 (**a**) Virtual Earth image (Google earth © 2012 Cnes/Spot Image) and (**b**) 2003–2005 average MLI in descending mode of Rio Taruga. (**c**) Google Maps view of *puquio* San Carlos (© 2013 DigitalGlobe Map data) (modified from Tapete et al. 2013b)

within the desert between the Rio Nazca and the Pampa de Chauchilla (see also Lasaponara & Masini, 2012). Among other features, a linear cyan one was found in correspondence with the track of a young *puquio* (for further detail the reader can refer to Tapete et al. 2013b).

Average MLI over the Taruga Valley allows the identification of the still functioning *puquios* Santa María and San Carlos, as well as of the disused *puquio* Camotal. The latter is distinguished based on different σ^0 likely due to its condition of abandonment (Fig. 5).

The capability of SAR imagery to support the recognition of ancient hydraulic systems (as also proven by other studies in wet regions, such as Moore et al. 2007) opens perspectives in water resource management from space. Impacts on arid cultural landscapes facing drought can be enormous for local communities. Furthermore, the assessment of the current condition of archaeological features like the *puquios* can inform on the potential impacts of climate change and desertification.

With this regard, high resolution SAR imagery, such as those from recently launched space-borne radar sensors, is expected to provide the most suitable scale of investigation. Nevertheless, an obvious shortcoming is represented by the cost of this type of imagery, with consequent constraints on the actual exploitation for monitoring activities.

From the point of view of scientific investigation over the Nasca region, Baade and Schmullius (2010), for instance, have recently discussed advantages and limits of TerraSAR-X products for multi-scale studies over the Rio Grande drainage basin.

Tapete et al. (in press) have shown the benefits deriving from the unprecedented level of spatial resolution offered by SpotLight and High Resolution SpotLight beam modes of TerraSAR-X and TanDEM-X satellites for local-scale applications over the archaeological landscape of Nasca. Surface features are already appreciable within the SAR images visualised based on their amplitude values.

Concluding Remarks

This study with ENVISAT ASAR data forms the basis for further investigations with other archive (i.e. C-band ERS-1/2) and recently to newly acquired imagery (i.e. TerraSAR-X). This amplitude-based approach complements successfully those exploiting interferometric coherence and phase, and can support a wide range of remote sensing activities including, but not limited to: (1) monitoring of land surface processes which can trigger natural hazards potentially damaging cultural and natural heritage; (2) environmental assessment from regional to local scale; and (3) understanding of past (and future) water resource management strategies. Further research will be also conducted by the authors with high resolution X-band imagery in the framework of the TSX-Archive-2012 LAN1881 project.

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References

Baade J, Schmullius CC (2010) Interferometric microrelief sensing with TerraSAR-X – first results. IEEE Trans Geosci Rem Sens 48(2):965–970

Cigna F, Tapete D, Lasaponara R, Masini M (2013) Amplitude change detection with ENVISAT ASAR to image the cultural landscape of the Nasca region, Peru. Archaeol Prospect 20(2):117–131. doi:10.1002/arp.1451

ESA (2013) Radar and SAR Glossary. https://earth.esa.int/handbooks/asar/CNTR5-2.htm. Last accessed 26 Nov 2013

Lasaponara R, Masini N (2012) Following the ancient Nasca puquios from space. In: Lasaponara R, Masini N (eds) Satellite remote sensing. A new tool for archaeology. Springer, Berlin, pp 269–289. ISBN 978-90-481-8801-7

Lefort A, Grippa M, Walker N, Stewart LJ, Woodhouse I (2004) Change detection across the Nasca pampa using spaceborne SAR interferometry. Int J Rem Sens 25(10):1799–1803

Masini N, Lasaponara R, Rizzo E, Orefici G (2012) Integrated remote sensing approach in Cahuachi (Peru): studies and results of the ITACA Mission (2007–2010). In: Lasaponara R, Masini N (eds) Satellite remote sensing. A new tool for archaeology. Springer, Berlin, pp 307–344. ISBN 978-90-481-8801-7

Moore E, Freeman T, Hensley S (2007) Spaceborne and airborne radar at Angkor: introducing new technology to the ancient site. In: Wiseman J, El-Baz F (eds) Remote sensing in archaeology. Interdisciplinary contributions. Springer, Berlin, pp 185–216. ISBN 978-0-387-44453-6

Ruescas AB, Delgado JM, Costantini F, Sarti F (2009) Change detection by interferometric coherence in Nasca Lines, Peru (1997–2004). In: Fringe 2009, 30 November to 4 December, ESRIN, Frascati, European Space Agency SP-677

Tapete D, Fanti R, Cecchi R, Petrangeli P, Casagli N (2012) Satellite radar interferometry for monitoring and early-stage warning of structural instability in archaeological sites. J Geophys Eng 9(4):S10–S25. doi:10.1088/1742-2132/9/4/S10

Tapete D, Casagli N, Fanti R (2013a) Radar interferometry for early stage warning of monuments at risk. In: Margottini C et al (eds) Early warning, instrumentation and monitoring, vol 2. Springer, Berlin, pp 619–625

Tapete D, Cigna F, Masini N, Lasaponara R (2013b) Prospection and monitoring of the archaeological heritage of Nasca, Peru, with ENVISAT ASAR. Archaeol Prospect 20(2):133–147. doi:10.1002/arp.1449

Tapete D, Cigna F, Lasaponara R, Masini N (in press) Multi-scale detection of changing cultural landscapes in Nasca (Peru) through ENVISAT ASAR and TerraSAR-X. In: IAEG congress proceedings, Springer, 6 pp