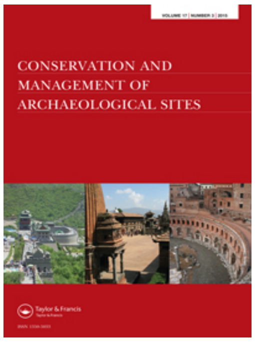

Conservation and Management of Archaeological Sites

ISSN: 1350-5033 (Print) 1753-5522 (Online) Journal homepage: http://www.tandfonline.com/loi/ycma20

The Measurement by Airborne Synthetic Aperture Radar (SAR) of Disturbance Within the Nasca World Heritage Site

Bruce D. Chapman, Douglas C. Comer, Johny A. Isla & Helaine Silverman

To cite this article: Bruce D. Chapman, Douglas C. Comer, Johny A. Isla & Helaine Silverman (2015) The Measurement by Airborne Synthetic Aperture Radar (SAR) of Disturbance Within the Nasca World Heritage Site, Conservation and Management of Archaeological Sites, 17:3, 270-286, DOI: 10.1080/13505033.2015.1129801

To link to this article: http://dx.doi.org/10.1080/13505033.2015.1129801

Published online: 20 Apr 2016.

CONSERVATION AND MGMT OF ARCH. SITES, Vol. 17 No. 3, March, 2016, 270–286

The Measurement by Airborne Synthetic Aperture Radar (SAR) of Disturbance Within the Nasca World Heritage Site

Bruce D. Chapman
Jet Propulsion Laboratory, California Institute of Technology, USA

Douglas C. Comer
Cultural Site Research and Management, USA

Johny A. Isla
Ministry of Culture, Peru

Helaine Silverman
Department of Anthropology, University of Illinois at Urbana-Champaign, USA

In this paper we report on our use of Synthetic Aperture Radar (SAR) as a means of monitoring the Lines and Geoglyphs of Nasca and Pampas de Jumana World Heritage Site in Peru, where the colossal ground drawings, popularly known as the Nasca Lines, are found. Our research to date indicates that the environment in which the Nasca geoglyphs are found, and the nature of the geoglyphs themselves, are suited perfectly for investigation by SAR. SAR also provides a new and valuable tool for understanding the human activities and natural processes that have damaged the geoglyphs and which, unchecked, will continue to do so in the future. Further, SAR can be used to categorize geoglyphs according to structural differences and similarities in ways that have heretofore not been possible, thereby serving as a basis for a geoglyph catalogue.

KEYWORDS Nasca, geoglyphs, Synthetic Aperture Radar (SAR), Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR), remote sensing, World Heritage Sites, archaeology, heritage management, monitoring

 DOI 10.1080/13505033.2015.1129801

Introduction

The colossal geoglyphs (ground drawings), popularly known as the Nasca Lines, are found on the dry coastal plateau, or *pampa*, of southern Peru as well as on valley hillsides bordering the *pampa*. They consist largely of tracings of animals at a huge scale as well as giant trapezoids, quadrangles, spirals, and a plethora of unerringly straight lines. The most spectacular of them lie within an area designated in 1994 as a World Heritage Site, Lines and Geoglyphs of Nasca and Pampas de Jumana.[1] In this paper we refer to ground marks, regardless of form, as geoglyphs except when citing the United Nations Educational, Scientific and Cultural Organization (UNESCO) or using Peruvian popular terminology. Most of the geoglyphs were made by the people of the Nasca culture between the years 50 and 650 AD (Unkel et al., 2012), though a small percentage were created by earlier societies that date to time periods such as Paracas and Topará (for an overview, see Lambers, 2006; Reinhard, 1986; Reindel et al., 2006; Silverman, 1990; 2002; Silverman & Browne, 1991; Silverman & Proulx, 2002). Those within the World Heritage Site are predominantly Nasca.

As the review of the nomination dossier for the World Heritage Site by the International Committee on Monuments and Sites (ICOMOS), which advises UNESCO on cultural matters, stated: 'There are many other examples in the world's archaeological record of geoglyphs of this kind, in the Americas and in Europe. However, none of these compares remotely with the extent, diversity, and long duration of the Nasca Lines' (ICOMOS, 1993: 96). Further, there are ample indications that the Nasca Lines are considered by the citizens of Peru to be an extremely important part of their heritage, and a reference point for national identity; the hummingbird geoglyph is represented on Peruvian currency and the spiral Nasca geoglyph is incorporated into Peru's nation-brand logo. Notwithstanding their worldwide acclaim and appreciation by the Peruvian public, however, the geoglyphs of the *pampa* have suffered terrible abuse since their popularization, which began in earnest in the 1940s with the advent of aircraft reconnaissance. They have been damaged in many ways, amongst them by cars whose drivers have sought to find them; by a Peruvian utility seeking a shortcut across the *pampa*; by Greenpeace during an event in 2014 (Greenpeace, 2015; Streep, 2015); and by natural events, such as flooding, especially during El Niño years.

In this paper we report on our use of Synthetic Aperture Radar (SAR) as a means of monitoring this especially sensitive World Heritage Site. Our research and findings to date suggest that the environment in which the Nasca geoglyphs are found and the nature of the geoglyphs themselves are ideally suited for the use of SAR as a new and valuable tool for understanding the human activities and natural processes that have produced damage to the geoglyphs and which, unchecked, will continue to do so in the future; further, that these factors are also such that SAR can be used to differentiate geoglyphs structurally in ways that have heretofore not been possible.

SAR data were acquired during the course of two South America campaigns, in 2013 and 2015, by Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR).[2] UAVSAR is the National Aeronautics and Space Administration (NASA) / Jet Propulsion Laboratory (JPL) L-band airborne SAR platform that has been in operation since 2009 (Fore et al., 2015). UAVSAR is designed to collect fully polarimetric SAR data on an aircraft able to fly near-exact-repeat flight lines for interferometry research and applications. UAVSAR, funded by NASA to conduct research for the NASA Science Mission Directorate, has a resolution of about 2 m.

The L-band Synthetic Aperture Radar (SAR) data were collected by the NASA UAVSAR platform almost exactly two years apart, on 19 March 2013 and on 21 March 2015. The second of the two flights was conducted to see if the production of a very high-resolution decorrelation image (described below) could detect and gauge the degree of any disturbance to the geoglyphs. A test case was fortuitously, if unfortunately, offered by the placement of a message by the environmental activism organization Greenpeace near the hummingbird geoglyph in December 2014 (Streep, 2015). Because of the geoglyphs' extreme fragility, access to this area had been prohibited for decades before this incident (although this has not completely stopped unpermitted access). The hummingbird geoglyph was one of the most pristine in the World Heritage Site.

After examination of the decorrelation image, it became apparent that UAVSAR data could be used not only to evaluate damage to the hummingbird geoglyph and the area immediately around it, but also to detect other ways in which the Nasca Lines have been disturbed, and, more importantly, could be further disturbed in the future. Also, it became clear that SAR returns can be analysed in ways that would provide a structural catalogue of the geoglyphs within the World Heritage Site.

Therefore, our ongoing research will be used to assess the capability of high-resolution SAR data to discern the characteristics of these geoglyphs according to differential backscatter values that that can be statistically grouped according to structural similarities that differ by time of construction and function, and the capacity of interferometric SAR data to identify areas that have been damaged or disturbed or are at risk of damage by human activities and the elements.

These capabilities will be used to accomplish the objectives listed below. We report most fully here on the first of these. Given the successful application of SAR technology to this first objective, the other two appear to be very feasible:

- Identification and evaluation of the extent of damage produced by the installation of the Greenpeace message in December 2014.
- Identification of risk areas and recommendations for risk reduction. The analysis would delineate areas where human or natural processes have damaged geoglyphs in the past and might lead to further degradation unless the processes are arrested. This would be used to identify steps that should be taken in order to avoid or minimize disturbance of the Nasca geoglyphs. Of the greatest concern is damage that might result from flooding, particularly the potential for severe flooding associated with El Niño.
- A structural catalogue of geoglyphs. The structural catalogue will be developed by a statistical clustering analysis of SAR backscatter. This will be used to provide dates and suggest functions for geoglyphs having distinctly different structures. There is also an important preservation component to this objective: the Nasca geoglyphs cannot be well protected without a definitive catalogue describing their current locations and characteristics. The catalogue will utilize both SAR and optical remote sensing data to delineate the Nasca geoglyphs.

Characteristics of Nasca geoglyphs

The Nasca geoglyphs are found on the sloping desert plain or pampa between the Nasca and Ingenio Valleys in southern Peru, and on the hillsides of the Río Grande de Nasca drainage, and on the smaller *pampas* in and between other nearby valleys (Silverman, 2002). The World Heritage Site in which most Nasca geoglyphs are located encompasses a 450 km^2 area.[3] While some geoglyphs lie outside the boundaries of the World Heritage Site, the *pampas* of Nasca and Palpa contain those that at time of inscription were considered to be the most outstanding from archaeological, historical, and aesthetic standpoints. Periodically, new geoglyphs are discovered on the slopes and hills of the Nasca and Palpa area. Nasca site managers, however, are aware of the fact that *new* geoglyphs have been constructed in recent years: for example, experimental reproduction of Nasca geoglyphs by filmmakers is well known to archaeologists who have worked in the area for many years. A structural catalogue of the Nasca Lines (objective 3 in the ongoing analysis) might be able to differentiate such recent construction from ones that are ancient, beyond the memory of scholars with first-hand knowledge.

Three types of geoglyphs are commonly found in the World Heritage Site: *biomorphic* figures (such as a hummingbird, a monkey, a whale, and many other animal forms); *geometric geoglyphs* (such as trapezoids, quadrangles, and zigzags); and *lineal geoglyphs* (long lines, each of unvarying width). While the spiral geoglyphs may be more properly associated with the geometric geoglyphs, their physical and conceptual nature is more similar to the biomorphic figures (for instance, the tail of the monkey geoglyph). A fourth type is now sometimes found: modern-era geoglyphs made in imitation of the Nasca-era figures.

There are many theories as to the function and meaning of these geoglyphs to the people who made them: astronomical significance that relates the geoglyphs to celestial objects or seasons; worship of mountain deities and associated veneration of water, weather and fertility; the delineation of the flow of water across the *pampa*; places and paths to be walked upon in a ritual or profane way; pathways used by pilgrims; as a locus of gatherings and ritual activities; a place for ritual functions such as funerals; and as linkages to subterranean water sources (see summary of theories in Lambers, 2006).

A number of authors (e.g. Clarkson, 1990; Lambers, 2006; Reinhard, 1986; Silverman, 1990; 2002; Silverman & Browne, 1991) have demonstrated that some geoglyph types can be associated with a specific time period. They use datable fineware ceramics found in association with geoglyphs or tight iconographic evidence based on comparisons of the biomorphs with motifs on Nasca pottery. There is substantial agreement among geoglyph scholars that the lineal geoglyphs appear to have been made throughout the whole time span of the Nasca era, while the biomorphic figures and spiral shapes are associated with early Nasca times. There are clusters in time associated with particular geometric shapes, though they persist throughout the Nasca era. Lambers (2006) sees evidence for some chronological differences in geographic location. He suggests that the geoglyphs in the Palpa area (one of the valleys in the Río Grande de Nasca drainage) are likely to date from an earlier time period, perhaps associated with the Paracas period (which predates the Nasca).

The vast majority of geoglyphs were made by a subtractive technique, whereby the small, angular rocks covering the ground surface were removed from the interior of the geoglyph shape, revealing lighter coloured subsoil, and the removed rocks were then placed as a border or berm around the cleared area (Silverman, 2002). Clearly, by their construction technique the geoglyphs are extremely fragile.

Because the geoglyphs are large (measuring from 20 m to several kilometres in length), their shapes are not always completely discernible from the ground. In contrast, the geoglyphs are readily visible from the air, leading to a proliferation of popular media attributions of the phenomenon to extraterrestrials (e.g. Von Däniken, 1970).

The geoglyphs were likely maintained by the groups that made them (Silverman, 1990), but disuse over decades and even centuries resulted in impairment of their ground-level visibility, exacerbated by inflation and deflation of the geoglyphs caused by material blowing across the *pampa* in this windy environment. Furthermore, the geoglyphs are subject to damage not just from wind, rain, and floods, but also from damage caused by the encroachment of modern life. The Pan-American Highway bisects the *pampa* thereby giving undesirable access to it. Various farming villages and towns line the valleys on either side of the pampa and the bustling tourist city of Nazca is at the eastern apex of the pampa. In an attempt to curb 'line hunting', a viewing tower was erected along the highway some decades ago offering a panorama of several biomorphic geoglyphs, and a short road off the Pan-American Highway lets visitors reach a low hill from which multiple lines radiate (especially, Aveni, 1990). With a limited budget for guards, the Ministry of Culture has difficulty preventing ingress to the *pampa*, thus hampering the protection of this remarkable World Heritage Site.

Remote sensing data and results

Because some of the lines themselves and borders (berms) of other geoglyphs are less than a metre or two in width, remote sensing data from space has only recently been effective for delineating them. Before 2000, aerial photographs were the most effective. However, there are now several commercial optical sensors with a resolution better than 1 m, such as IKONOS, Quickbird, Pleiades, and Worldview-2. Many samples of these images are readily available in Google Earth. Google Earth also allows the user to inspect time sequences of images within their image catalogue.

Spaceborne SAR data has also been used to study the geoglyphs, such as the C-band Envisat ASAR data (Tapete et al., 2013) and X-band TerraSAR-X (Braun, 2010), but the relatively low resolution of these sensors prevented any significant use of these data. The UAVSAR is a NASA/JPL fully polarimetric airborne SAR with a wavelength of 23 cm, which falls in the L-band of the electromagnetic spectrum. Operational since 2009, it flies on board the NASA Armstrong Gulfstream C-20A aircraft. The aircraft has been specially modified to fly extremely precise planned flight paths such that it can repeat the same flight path even years later, only rarely diverging from the planned flight path by more than 5 m over hundreds of kilometres of flight (Figure 1). This allows the data from UAVSAR to be interfered with a near zero baseline between observations (called InSAR).

The 160-km flight path in the study area was acquired by UAVSAR on 19 March 2013 and again on 21 March 2015 (Figure 2). The cross-track image swath is about 20 km. The UAVSAR data may be processed as 'Single Look Complex' (SLC) image files where each pixel represents the magnitude and phase of the backscattered radio waves. Using known point targets as calibrators, it has been found that the UAVSAR image resolution is 2.5 m in the cross-track direction and better than 1 m in the along-track direction (Fore et al., 2015). The imagery is sampled in natural radar coordinates with a pixel spacing of 1.6 m in the cross-track direction by 0.6 m in the along-track direction. Since the pixel spacing is smaller in the along-track direction, the pixels were made square by spatially averaging about 3 pixels in the along-track direction for every 1 pixel in the cross-track direction for the final image products shown here.

The high-resolution optical imagery in Google Earth and the UAVSAR imagery from the HH (horizontal polarization on both transmit and receive) polarimetric

FIGURE 1 UAVSAR in flight onboard the NASA-Armstrong C-20A aircraft. The side-looking SAR is contained within the white pod beneath the aircraft. (Image courtesy of NASA)

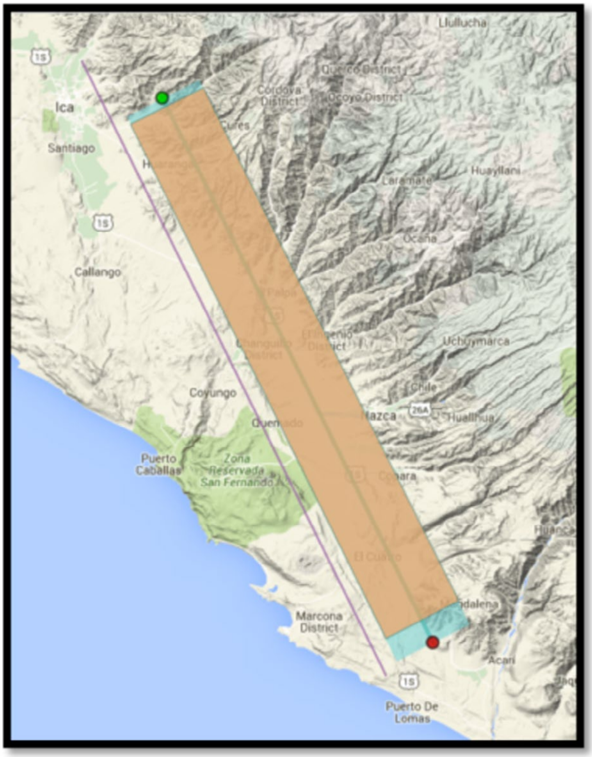

Figure 2 Flight path of UAVSAR showing area imaged (shaded rectangle). The aircraft flew at a southeastern heading of 153 degrees, at an altitude of 41,000 ft. SAR is side-looking, so the imaged area is to the left of the flight path. This flight path, imaging over 3000 km², was flown in just 12 minutes. (Base: Google Map © 2015 Google)

FIGURE 3 Biomorphic/spiral geoglyph. The (green) line Indicates 100 M. North Is To The Top. (A) Spiral Shape Is Shown At Top, As Well As Other Biomorphic And Geometric Geoglyphs (Google Earth Image © 2015 Digital Globe). (B) Uavsar Hh Polarization Image. While Some Of The Geometric Geoglyphs Are Visible, The Spiral Geoglyph Is Not. The Geometric Geoglyphs Are Less Distinct Here Than In Other Areas.

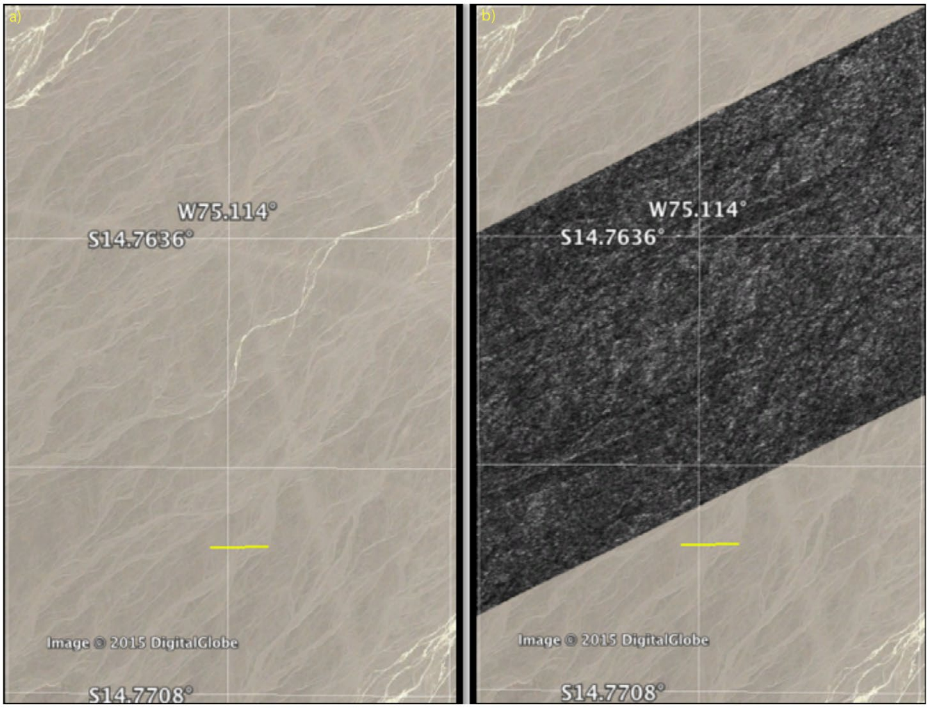

FIGURE 4 Geometric geoglyph. The (yellow) line indicates 100 m. North is to the top. (a) The geoglyphs are not readily visible in the optical image at this zoom level. Google Earth image © 2015 Digital Globe. (b) UAVSAR image overlaid in Google Earth. Two geometric geoglyphs are readily visible.

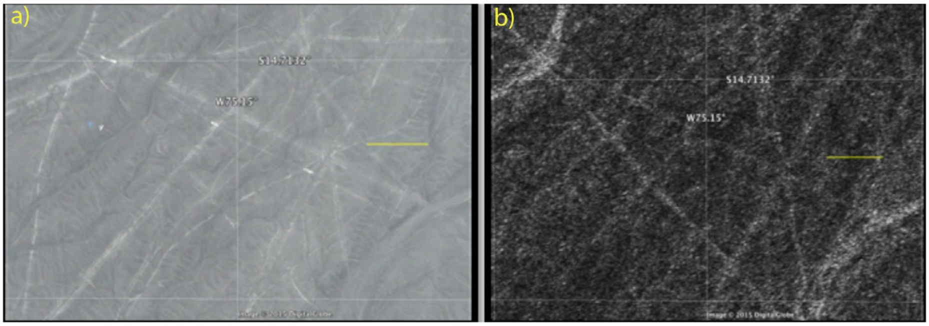

Figure 5 Lineal geoglyphs. The (yellow) line indicates 100 m. North is to the top. (a) Google Earth image © 2015 Digital Globe showing lineal geoglyphs, some intersecting toward the middle right of the image. (b) UAVSAR image overlaid in Google Earth; most but not all lines are clearly visible, where some linear features might not be geoglyphs but may instead be modern paths or tracks. Clearly identifiable tyre tracks visible in the optical image are not visible in the UAVSAR image. Also visible in both images are some of the dry creek-beds, which tend to have more rocks than the surrounding plains.

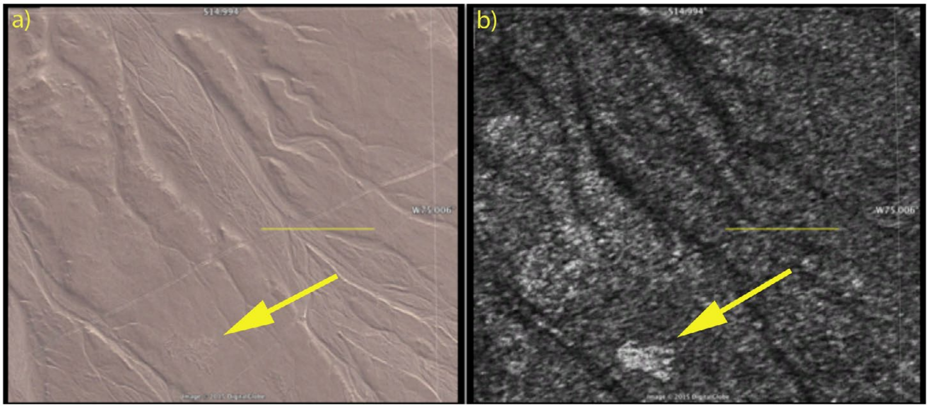

Figure 6 Modern-era geoglyph. The (yellow) line indicates 100 m. North is to the top. (a) Google Earth image © 2015 Digital Globe showing modern-era geoglyph and centre bottom of the image as well as other fainter modern-era figures. This location is outside the protected zone of the World Heritage Site, but is within the area that the Nasca geoglyphs are found. (b) UAVSAR image overlaid in Google Earth, where the modern-era figure is prominent.

channel can be compared (Figures 3–6). By examination of optical or SAR imagery alone, it is difficult in some cases to distinguish the Nasca geoglyphs from modern features such as unpaved roads, tyre tracks, unrelated paths, and some forms of development by the nearby communities. In addition, some geoglyphs are simply difficult to see in the optical imagery due to lack in colour contrast between the geoglyphs and the surrounding terrain. In these cases, ground verification and aerial reconnaissance driven by the remote sensing data can be invaluable. Often geoglyphs not initially discernible in the Google Earth imagery but visible in the SAR imagery can be seen in the Google Earth imagery by zooming in to full resolution of the optical image at the indicated location.

Different visualizations of an area with geometric geoglyphs enable us to see that the edges of the geometric geoglyph in the SAR images are bright (Figure 7). This is predominately due to the increased roughness of the edges due to the mound of rocks piled there (Figure 8), but is also additionally enhanced if the radar look direction is oriented parallel to the flight path (Figure 9). With this orientation the fraction of diffusely scattered radiation is more preferentially scattered back towards the side-looking

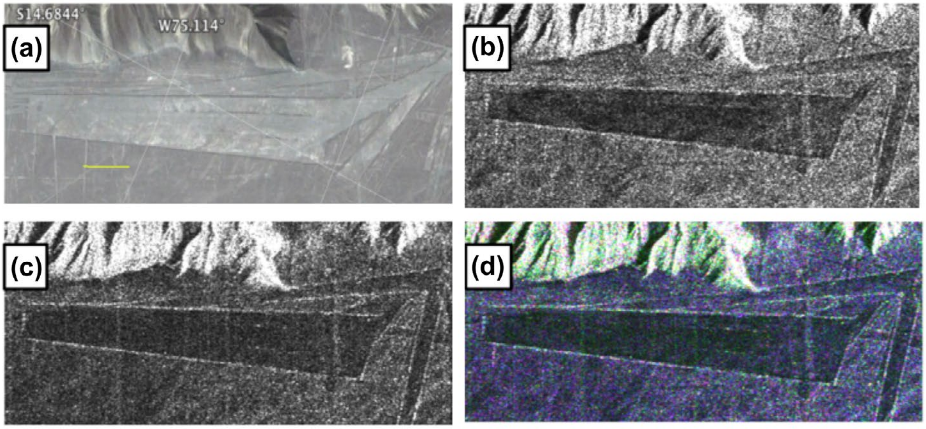

Figure 7 Geometric geoglyph. North towards the upper right. (a) Google Earth image © 2015 Digital Globe showing geometric geoglyphs. The (yellow) line indicates 100 m. (b) HH polarization image. (c) HV polarization image. (d) Colour composite of HH (red), HV (green), and VV (blue) (vertically polarized on transmit and receive).

Figure 8 Ground photo (taken 23 March 2015) of the edge of a typical geometric geoglyph. In this case, the mound of rocks at the edge was about 1 m wide and rose about 20 cm from the surrounding terrain.

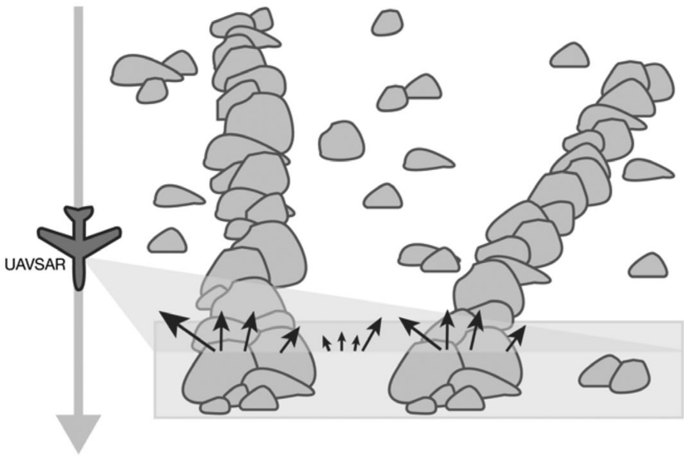

Figure 9 Illustration of scattering of radio waves from UAVSAR by rocks within the Nasca World Heritage Site, where the size of the arrows roughly illustrates the relative energy reflected in that direction. While berms at the edge of a geoglyph, if parallel to the flight track, can further enhance the backscattered power, the dominant scattering mechanism at L-band wavelengths for the Nasca World Heritage Site is rough surface scatter, where the backscattered power is mostly a function of the rock density. In areas where the rock density is lower, the specular scatter away from the radar antenna results in lower backscattered power.

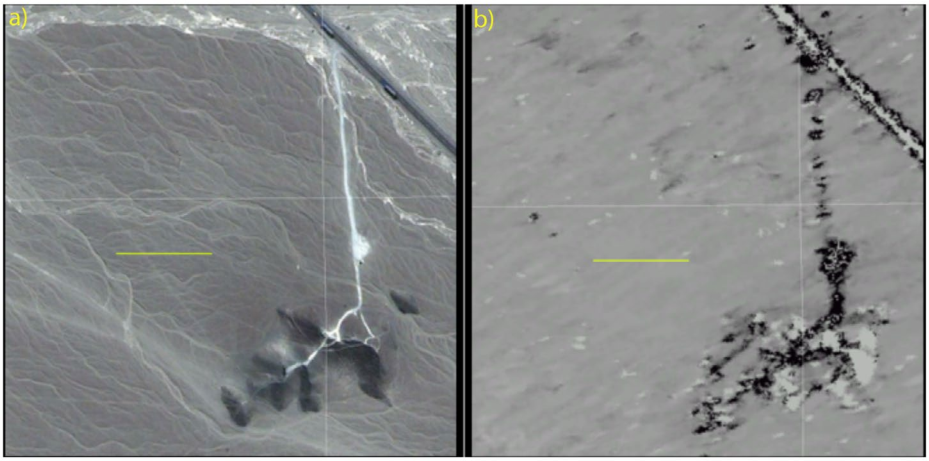

Figure 10 The (yellow) line indicates 100 m. North is to the top. Coordinates are (14.707 S, 75.103 W). (a) Google Earth image © 2015 Digital Globe image showing Pan-American Highway in upper right, and unpaved road from the highway to a hilly area for viewing the geoglyphs. (b) Calibrated correlation image from UAVSAR overlaid in Google Earth. Black corresponds to decorrelation, typically due to disturbance between the two observations (In March 2013 and March 2015), while grey and light grey correspond to areas with minimal decorrelation.

UAVSAR. Meanwhile, the interior of the geoglyph is darker due to the relatively sparse rock density, which results in reduced surface roughness apparent to the L-band radiation and therefore reduced backscattered radar power. This is especially true for the HH and VV polarimetric image.

We observe that only the geometric and lineal geoglyphs are often discernible in the UAVSAR imagery. On those occasions where the geometric and lineal geoglyphs are not easily visible in the SAR imagery (e.g. Figure 3b), the rock density defining the geoglyphs is likely not substantially different than that of the surrounding terrain. It is interesting to note that the lineal geoglyphs are mainly distinguishable in the SAR imagery if they are characterized by a concentration of rocks along the path. Tyre tracks and other types of paths that simply beat down the path are likely to be less discernible in the SAR imagery, but are just as easily visible in the optical imagery. The biomorphic and spiral geoglyphs are not clearly distinguishable because of the smaller size of the outline of the figures and the general lack of a mound of rock; they are mainly visible to the eye because of the absence of rock in the interior of the path rather than the presence of a mound of rocks. The 2-m resolution of UAVSAR is too low to discern the more subtle change in backscatter resulting from the clearing of rocks from the path defining the biomorphic geoglyphs (and spirals). Contrarily, we note that despite the 2-m resolution of the radar, a small bright radar reflector (such as a properly oriented rock or mound of rocks) can be visible in the image even if is smaller than 2 m in size.

To investigate the sensitivity of the UAVSAR data to ground disturbance, we first co-register pixel for pixel the SLC images from the both flights. The calibrated interferometric correlation γ_{cal} can be obtained by equation 1 (Zebker & Villasenor, 1992).

$$\gamma_{cal} = \frac{|< E_1 E_2^* >|}{\sqrt{< E_1 E_1^* >< E_2 E_2^* >}}(1 + SNR^{-1}) \tag{1}$$

Where E_1 and E_2 are the SLC estimates of the calibrated complex electric field for the two data takes and the ensemble average is over a given number of statistical looks. The * indicates the complex conjugate. The SNR is the signal-to-noise ratio where the noise is given by an empirically derived quadratic fit to the noise-equivalent radar backscattered power of the image. γ_{cal} can vary between 0 (complete decorrelation between the two images) and 1 (no decorrelation between the images). The normalization by the SNR can result in some areas having a correlation greater than 1.

We employed an algorithm to find the optimum ensemble average for each pixel when calculating the correlation, using software developed at JPL (Smullen et al., 2015). Based on pixel similarity, this method preserves the high resolution of the UAVSAR imagery as much as possible while maximizing the number of looks (Deledalle et al., 2011).

The general property of the correlation data is that areas that have vegetation have much lower values than areas without vegetation. Open water also decorrelates, as the scattering of the radio waves is highly variable over water. The desert areas of the Nasca geoglyphs are almost completely lifeless, and therefore, absent of any other effect, the correlation should be close to 1. In areas where the slopes are steep, there are often edges of decorrelation where erosion may be occurring.

Figure 10 shows the calibrated correlation image over a tourist attraction on the Nasca *pampa*, where visitors are invited to exit from the Pan-American Highway and drive across a dirt road to a small mound of hills, where they may observe some of the geoglyphs from a slightly elevated position (see Aveni, 1990). As can be seen, the correlation is reduced along this road, as well as locations on the hill where visitors might walk about and take in the view of the geoglyphs. In a region along the Pan-American Highway, where many creek-beds dominate the usually arid landscape (Figure 11), the decorrelation does not just correspond to where local vegetation grew and where water was flowing at the time of one of the two acquisitions, but also includes areas where water disturbed the creek-beds at some point between the two observations. A protected area in the Nasca World Heritage Site experienced apparent disturbance between the two observations (Figure 12): the UAVSAR correlation image shows that three unpaved paths in this area have been disturbed, probably due to vehicular traffic; a dry creek-bed shows evidence of erosion; and the movement of power lines between observations is very evident in the correlation image.

Finally, one of the well-known Nasca geoglyphs, the hummingbird, was the site of a protest by Greenpeace in December 2014 (Streep, 2015). During this protest, approximately twenty people traversed a path from an unpaved road below the *pampa* to the

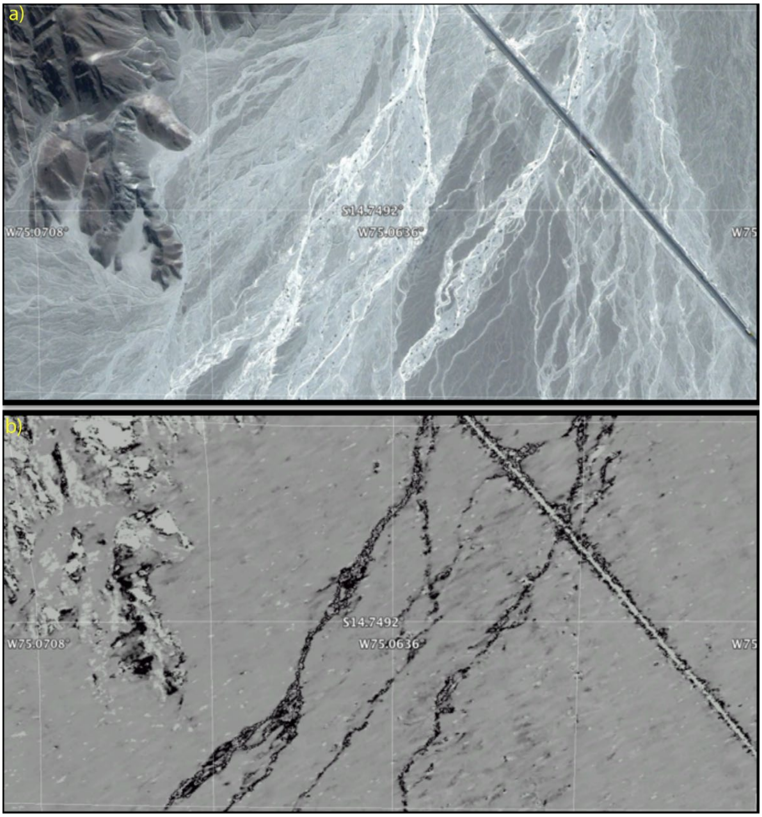

Figure 11 North is to the top. (a) Google Earth image © 2015 Digital Globe image showing Pan-American Highway in upper right and a landscape with many (usually) dry creek-beds within the protected zone. (b) UAVSAR correlation image overlaid in Google Earth where black corresponds to decorrelation, typically due to disturbance between the two observations (March 2013 – March 2015). We see that some, but not all, of the creek-beds are decorrelated. This is likely due to flooding, but not necessarily at the time of one of the two UAVSAR acquisitions. We also observe an unusual amount of decorrelation around the area near some hills towards the lower left of the image.

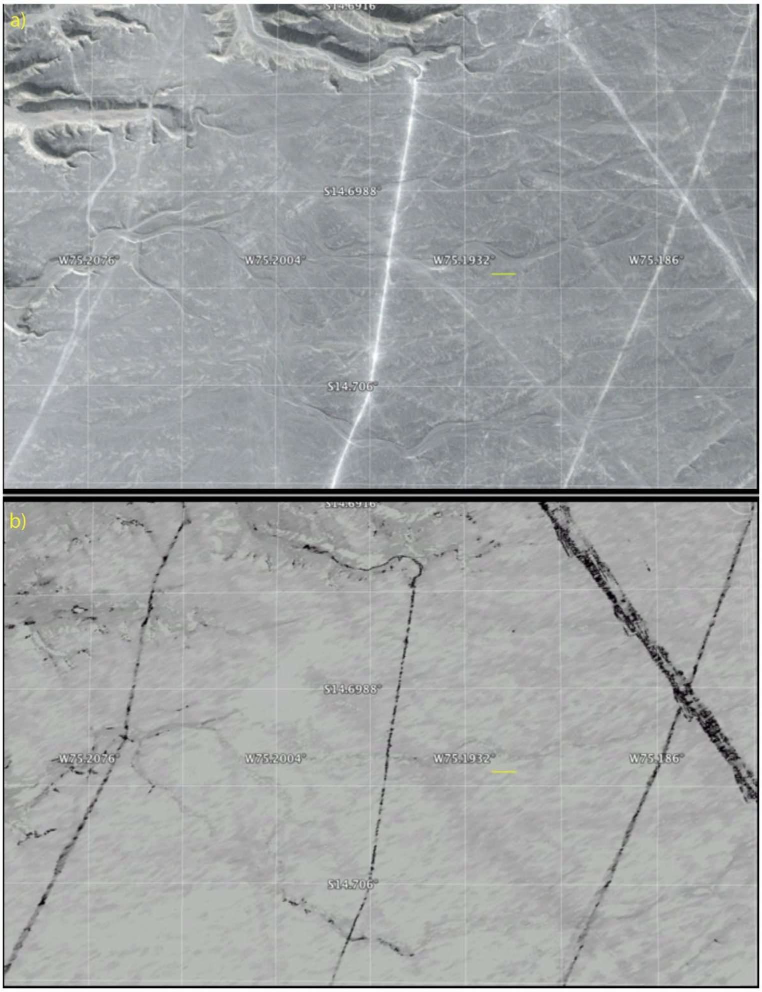

Figure 12 The (yellow) line indicates 100 m. North is to the top. (a) Google Earth image © 2015 Digital Globe image showing an area within the protected World Heritage Site traversed by dirt roads, power lines, and geoglyphs. (b) Calibrated correlation image from UAVSAR overlaid in Google Earth. Black corresponds to decorrelation, typically due to disturbance between the two observations (March 2013 – March 2015), while grey and light grey correspond to areas with minimal decorrelation. This image shows three unpaved roads within the protected portion of the Nasca World Heritage Site that have been disturbed, plus evidence of erosion along what is usually a dry creek-bed in the centre middle of the image. The power lines are in the upper right-hand portion of the image, where the decorrelation stands out due to the movement of the power lines between observations.

hummingbird geoglyph, and then over the next few hours placed a large protest banner immediately adjacent to it. A video shows the path taken by the protestors to the hummingbird geoglyph area,[4] where the protestors placed their equipment, and where the banners were placed (Mack, 2014). The correlation image (Figure 13) shows substantial decorrelation in those locations.

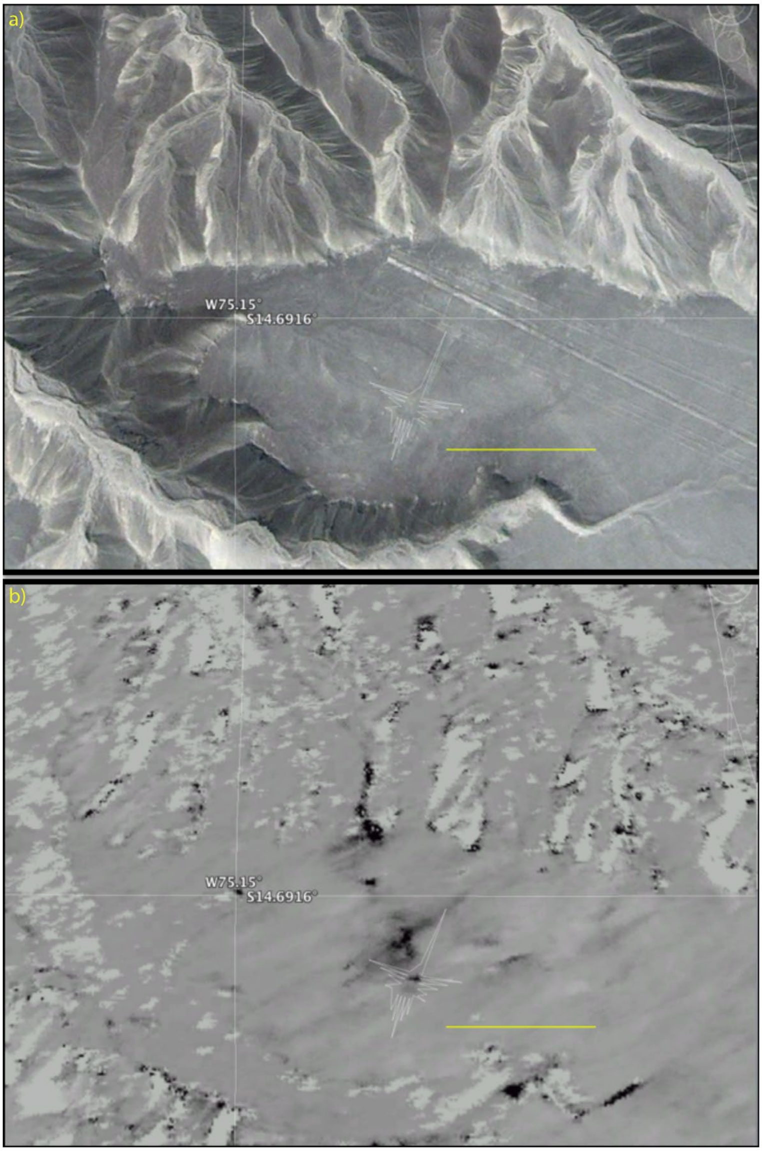

FIGURE 13 The (yellow) line indicates 100 m. North is to the top. (a) Google Earth image © 2015 Digital Globe image showing the area near the hummingbird geoglyph with an outline drawn of the approximate location of the hummingbird. (b) Calibrated correlation image from UAVSAR overlaid in Google Earth with an outline drawn showing the approximate location of the hummingbird. Black corresponds to decorrelation, typically due to disturbance between the two observations (March 2013 – March 2015), while grey and light grey correspond to areas with minimal decorrelation. This image shows the location of the hummingbird geoglyph. Five indications of disturbance are observed: (1) a path from the unpaved road to the North; (2) an area as one enters the pampa from below, where an online video shows that equipment and people congregated; (3) the area near the hummingbird geoglyph, in close approximation to where the Greenpeace banners where placed; (4) decorrelation within the head of the hummingbird itself; and (5) ridgeline areas of decorrelation where the slope is large and natural erosion may be occurring.

Conclusion

We have used the NASA/JPL UAVSAR airborne SAR to investigate the use of high-resolution SAR for examining the condition of the Nasca geoglyphs in Peru and characterizing them according to structure. We have also used a repeat-pass interferometric pair of images, separated by two years, to investigate using UAVSAR to detect disturbance within the protected area of this World Heritage Site.

We find that the polarimetric images are sensitive to the boundaries and interior characteristics of the geometric Nasca geoglyphs. In some areas where the geoglyphs are optically indistinct, we find that they can be quite clearly visible in the UAVSAR imagery. We also find that the structural characteristics of the geoglyphs (the size and height of the mounds on the boundary, and the relative scarcity of rocks in the interior of the geoglyphs) can be ascertained by analysis of the UAVSAR data.

We also find that the calibrated correlation data from the interferometic pair of images, acquired two years apart, is quite sensitive to changes in the surface of the delicate desert *pampas* surrounding the geoglyphs. We see evidence of disturbance: by visitors use of unpaved roads in the protected zone of the World Heritage Site; erosion of intermittent creek-beds and sheet erosion of adjacent areas; and, next to and within the hummingbird geoglyph, in and near areas where Greenpeace personnel placed large protest banners.

Due to the high resolution of the data, the data volume is large and the geo-referencing of the data is complex. These extremely large data sets will require access to exceptional computational capacity to organize. However, it seems clear that by continued exploration of this data we will be able to accomplish several related tasks: (1) to identify areas at risk of environmental degradation, as well as damage by human activities; (2) to develop a structural catalogue of geoglyphs that can be associated with certain times and functions; and (3) to prioritize management activities according to the degree to which certain geoglyphs are threatened.

Acknowledgements

We thank Craig Dobson for his support of this work through the NASA Space Archaeology programme. We thank the Ministry of Culture, Peru for their support; in particular, that of Minister Diana Alvarez Calderon Gallo, and former Vice-Minister Luis Jaime Castillo Butters. We also thank the NASA/JPL UAVSAR programme for the collection and processing of the SAR data. We thank Sarah Flores of JPL for illustrating Figure 9. This work was partially performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Notes

1 See http://whc.unesco.org/en/list/700 [accessed October 2015].

2 See http://uavsar.jpl.nasa.gov/ [accessed October 2015].

3 See map accessible via: http://whc.unesco.org/en/list/700/multiple=1&unique_number=828 [accessed October 2015].

4 YouTube: https://www.youtube.com/watch?v=RzavtWbjXow [accessed October 2015].

Orcid

Bruce D. *Chapman* http:// orcid.org/0000-0002-6054-7695

Bibliography

Aveni, A. 1990. Order in the Nasca Lines. In: A. F. Aveni, ed. *The Lines of Nazca*. Philadelphia, PA: Memoirs of the American Philosophical Society, Vol 183, pp. 41–113.

Braun, M. 2010. TerraSAR-X Image of the Month: The Nazca Lines in Peru. [online] [Accessed September 2015]. Available at: <http://www.dlr.de/en/desktopdefault.aspx/tabid-6215/10210_read-25333/10210_page-3/>.

Clarkson, P. B. 1990. The Archaeology of the Nazca Pampa: Environmental and Cultural Parameters. In: A. F. Aveni, ed. *The Lines of Nazca*. Philadelphia, PA: Memoirs of the American Philosophical Society, Vol 183, pp. 115–172.

Deledalle, C.-A., Denis, L. & Tupin, F. 2011. NL-InSAR: Nonlocal Interferogram Estimation. *IEEE Transactions on Geoscience and Remote Sensing* 49 (4): 1441–1452.

Fore, A. G., Chapman, B. D., Hawkins, B. P., Hensley, S., Jones, C. E., Michel, T. R. & Muellerschoen, R. J. 2015. UAVSAR Polarimetric Calibration. *IEEE Transactions on Geoscience and Remote Sensing* 53 (6): 3481–3491.

Greenpeace. 2015. Greenpeace Offers Apology for Nazca Lines Action. [online] [Accessed September 2015]. Available at: <http://www.greenpeace.org/international/en/news/features/Nazca-Timeline/>

ICOMOS. 1993. *Evaluation of the World Heritage List Nomination for the Lines and Geoglyphs of Nasca and Pampas De Jumana*. Paris, France: ICOMOS Documentation Centre. [online] [accessed October 2015]. Available at: http://whc.unesco.org/archive/advisory_body_evaluation/700.pdf

Lambers, K. 2006. *The Geoglyphs of Palpa: Documentation, Analysis and Interpretation*. Aichwald: Linden Soft.

Mack, D.. 2014. Greenpeace Nazca Lines Protest - Dec. 8, 2014. [online video] [Accessed September 2015]. Available at: https://www.youtube.com/watch?v=RzavtWbjXow.

Reindel, M., Isla, J. & Lambers, K. 2006. Los Geoglifos De Palpa: Documentación, Análisis Y Perspectivas. *Boletín De Lima* 143: 73–111.

Reinhard, J. 1986. A new perspective on their origin and meaning. Editorial Los Pinos; 2nd edition (1986), ISBN-13: 978-8489291171

Silverman, H. 1990. Beyond the Pampa: The Geoglyphs in the Valleys of Nazca. *National Geographic Research* 6 (4): 435–456.

Silverman, H. 2002. *Ancient Nasca Settlement and Society*. Iowa City: University of Iowa Press.

Silverman, H. & Browne, D. M. 1991. New Evidence for the Date of the Nazca Lines. *Antiquity* 65 (247): 208–220.

Silverman, H. & Proulx, D. 2002. *The Nasca*. Malden, MA: Blackwell.

Smullen, D., Kling, T., Ahmed, R., Agram, P. & Neumann, M.. 2015. *Non-Local InSAR Filtering; Refactoring for Performance and Scalability*. Pasadena, CA: Jet Propulsion Lab., Cal. Inst. Tech. Report. Aug. 15, 2015.

Streep, A. 2015. This Man is Greenpeace's Best Hope, *Outside Magazine*, March 13, 2015 [Accessed September 2015]. Available at: <http://www.outsideonline.com/1959936/man-greenpeaces-best-hope>.

Tapete, D., Cigna, F., Masini, N. & Lasponara, R. 2013. Prospection and Monitoring of the Archaeological Heritage of Nasca. *Peru, with ENVISAT ASAR, Archaeological Prospection* 20 (2): 133–147.

Unkel, I., Reindel, M., Gorbahn, G., Isla, J., Kromer, B. & Sossna, V. 2012. A Comprehensive Numerical Chronology for the Pre-Columbian Cultures of the Palpa Valleys, South Coast of Peru. *Journal of Archaeological Science* 39: 2294–2303.

Von Däniken, E. 1970. *Chariots of the Gods? Memories of the Future – Unsolved Mysteries of the past*. New York: G. P. Putnam's Sons.

Zebker, H. A. & Villasenor, J. 1992. Decorrelation in Interferometric Radar Echoes.*IEEE Transactions on Geoscience and Remote Sensing* 30: 950–959.

Notes on contributors

Bruce Chapman is a radar scientist in the sub-orbital radar science and engineering group at the NASA Jet Propulsion Laboratory. He is interested in the archaeological applications of SAR and other remote sensing methods.

Correspondence to: Bruce.D.Chapman@jpl.nasa.gov

Douglas C. Comer is President of Cultural Site Research and Management, has authored numerous works on technical applications in archaeology and heritage management, and has prepared management plans for many World Heritage Sites.

Johny Isla is an archaeologist at the Ministry of Culture, Peru where he directs the Management System for Cultural Heritage of Nasca and Palpa. He has conducted research with the German Archaeological Institute (DAI) and is Co-Director of the Nasca-Palpa Archaeological Project

Helaine Silverman is Professor of Anthropology at the University of Illinois and Director of the Collaborative for Cultural Heritage Management and Policy (CHAMP). She has published extensively on Nasca archaeology and cultural heritage.