ABSTRACT

Two interferometric pairs of Synthetic Aperture Radar (SAR) images are used to generate coherence images of the Nasca Lines Pampa area. The first coherence image is based on a pair of ERS-2 SAR data from 1997 and 1999; the second one is computed from two ENVISAT-ASAR (Advanced SAR) images from 2003 and 2004. The main objective is to study the changes in the coherence values in different parts of the area. Several different decorrelation factors contributing to a loss of coherency in a radar pair can be distinguished, and these include the temporal change in the ground properties and nature between the two satellite passes. In order to do this discrimination and interpretation, some ancillary data can be used, such as optical data from the Advanced Land Observing Satellite (ALOS), and meteorological data from the Global Precipitation Climatology Center (GPCC).

Figure 1. Area of study using a false RGB composition (AVNIR-2) and DEM ASTER

Radar coherence is normally used as measure of the quality of an interferogram [2], being associated to the phase difference noise. However, coherence has also a thematic value. In fact, it is a measure of the local decorrelation between two complex radar acquisitions. Several decorrelation factors contributing to a loss of coherency in a radar pair can be distinguished [3], as shown in the equation Eq. 1.

\[ \gamma = \gamma_{\text{proc}} \cdot \gamma_{\text{doppler}} \cdot \gamma_{\text{base}} \cdot \gamma_{\text{noise}} \cdot \gamma_{\text{phys}} \]  

Where \( \gamma_{\text{proc}} \) is related to the quality of the processing, \( \gamma_{\text{doppler}} \) is a factor due the difference between the mean Doppler frequencies in azimuth in the two complex images, \( \gamma_{\text{base}} \) is a factor due to the distance of the perpendicular baseline, \( \gamma_{\text{noise}} \) represents the loss of coherence due to thermal noise, and \( \gamma_{\text{phys}} \) represents the loss of coherence due to physical changes between the two acquisitions. For thematic applications of the coherence, this last factor is the one that must be observed and quantify. That means that we have to identify first which is the loss introduced by the \( \gamma_{\text{doppler}} \) and \( \gamma_{\text{base}} \) factors. For a same type of receptor, \( \gamma_{\text{proc}} \) and \( \gamma_{\text{noise}} \) are constant.

The factor with thematic information content (\( \gamma_{\text{phys}} \)) is linked to the local temporal decorrelation of the radar.
Table 1. Data used and its correspondent date

<table>
<thead>
<tr>
<th>SATELLITE</th>
<th>DATE</th>
<th>SENSOR</th>
<th>SPATIAL RES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS-2</td>
<td>23/09/1997</td>
<td>SAR</td>
<td>20 m</td>
</tr>
<tr>
<td></td>
<td>07/12/1999</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENVISAT-2</td>
<td>04/02/2003</td>
<td>ASAR</td>
<td>20 m</td>
</tr>
<tr>
<td></td>
<td>07/12/1999</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANVIR-2</td>
<td>09/06/2009</td>
<td>MS</td>
<td>10 m</td>
</tr>
<tr>
<td>(ALOS)</td>
<td>25/07/2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRISM</td>
<td>19/04/2007</td>
<td>PAN</td>
<td>2.5 m</td>
</tr>
<tr>
<td>(ALOS)</td>
<td>21/04/2008</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

reflection characteristics of the surface targeted between two observations, in two different times. This is related to a temporal change in the ground properties that could induce to variations of the phase and amplitude in the single look complex (SLC) data. The nature of changes related to a coherency loss must be analysed carefully and interpreted with the use of ancillary data [4]. In the present work, we carry on an individual interpretation of two coherence images, over a time interval spanning eight years and affected by at least two major ENSO events (1997-1998 and 2002-2003).

2. THE STUDY AREA

The Nasca geoglyphs are located in an alluvial plain, now part of the Atacama Desert, approx. 450 km south of Lima. This is one of the most arid areas of the world. Geoglyphs can be found in the flat plain and on the low Andean foothills that consist of ferruginous sand and gravel of a dark colour. The Nasca basin is transacted by a series of rivers running down the western slope of the Andes that can carry water only seasonally, following rainfalls in the highlands. Despite that, the valleys are fertile, thanks to sophisticated irrigation systems. The Nasca Pampa is a vast stretch of desert (approx. 220 square km) north of the town of Nasca (Fig. 1). The geoglyphs here were made by removing the dark gravels, revealing the underlying light colour strata. These marks on the land or drawings fall into two categories (UNESCO): natural forms like animals (birds between 50-280 m long, a spider 46 m long, a monkey 55 m long, a lizard 180 m long), flowers, plants, trees or fantastic figures and a few anthropomorphic figures (the Astronaut, the Man with the Hat, the Executioner); and the second category that comprises the lines, most of them several kilometres in length (20-25 km), and geometrical forms like rectangles and trapezoids. They first appeared in the Paracas Period (400-200 BC) and grew in number during the Early and Middle Nasca Period (0-450 AD). Following the end of the Nasca Culture (600 AD) the making of geoglyphs ceases. The whole landscape was declared World Cultural Heritage by UNESCO in 1994 (Law No. 24047/1985). Geomorphological investigations have shown that the regional climate gradually became dryer since Paracas times [5]. Due to climate irregularities, local rainfalls at wide temporal intervals resulted in substantial destruction of adobe constructions in the Nasca settlements. Therefore, it can be supposed that climatic irregularities and sudden rainfalls in a period of extreme aridity at the end of the Nasca period led to a destabilisation of the Nasca culture and finally to its decline.

3. DATA AND METHODS

3.1. Data used

For the extraction of the coherence images we used two pairs of interferometric data. The first coherence image was based on a pair of ERS-2 SAR data from 1997 and 1999 with a temporal baseline of 15 months and a perpendicular baseline of 541 m; the second one consisted of two ENVISAT-ASAR images from 2003 and 2004 with a temporal baseline of almost 22 months and a perpendicular baseline of 89 m. SAR and ASAR sensors work in band C (5.6 cm or 5.3 GHz), given a ground resolution of around 20 m pixel. We also used optical data as references to discriminate the different areas of interest: Advanced Land Observing Satellite Advanced Visible and Near Infrared Radiometer type 2 (ALOS AVNIR-2) and Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM). We also counted with the ASTER-DEM (AST14DEM, http://asterweb.jpl.nasa.gov/content/03_data/01_Data_Products/releaseDEM_relative.htm), with 30 m spatial resolution. For details see Tab. 1.
3.2. Methodology

An interferogram measures the phase difference between two images. The consequence of any factor inducing a coherence loss, including the loss induced by temporal decorrelation (temporal changes in the ground nature), is the degradation of part of the interferometric information. The coherence is defined as the measurement of the complex correlation between two complex radar images. It is a result of the estimation of the spatial correlation. The coherence can add complementary information to the amplitude image (land uses, erosion, human activities, water...) and it allows generating composed radar products, richer than the simple intensity. Loss of coherence is influenced by changes in the soil, but also by different geometric conditions in the image acquisition process. The coherence values ranges from 0, indicating that the interferometric phase is just noise, to 1 that shows a complete absence of phase noise. The exact relation between phase dispersion and coherence (\(\gamma\)) with a number of looks (NL) higher than four can be express by this mathematical approximation [6]:

\[
\sigma_\phi = \frac{1}{\sqrt{2NL}} \frac{\sqrt{1-\gamma^2}}{\gamma} \tag{2}
\]

Where \(\sigma_\phi \leq 12^\circ\) and NL is large and \(\gamma\) close to one. That is to say, the formula is suitable for coherence values higher than 0.2 and \(NL \geq 4\).

In order to obtain good coherence data we looked for pairs of images with low perpendicular baselines, considering less than 150 meters as the more appropriate. This condition is true in the second pair (ENVISAT-ASAR), but the first pair has a perpendicular baseline of 540 meters, more problematic if no digital elevation model (DEM) is available and the topography area is not very smooth. As we have seen before, certain loss of coherence is due to this effect of geometry decorrelation derived form the baseline distance (\(\gamma_{base}\)). For a determined class with a thickness value \(h\), the decorrelation factor changes with the thickness as can be see in Fig. 2. Those curves show how the orbital perpendicular baseline influences on the coherence for different thickness of a theoretical class uniformly distributed. If we considered our study area within the bare soil category, \(h=0\) m (it is desert), the difference between our image pair with a perpendicular baseline of 89 m and the image pair with 540 m would be of a maximum of 0.55. Therefore, we can manage the loss of coherence caused by the \(\gamma_{base}\) calculating the average difference of the coherence values found in both images and correct them adding the mean value extracted to the image with the highest baseline to cancel this bias.

The second parameter that can affect the quality of the coherence \(\gamma_{doppler}\) can be neglected in both interferometric pairs, since the acquisition Doppler was stable and constant in all acquisitions. For ERS-2 and ENVISAT pairs, the average Doppler normalized frequency of single look complex (SLC) images varies from -0.3 to 0.3. Only after January 2001 this changed for ERS-2 data, due to a degradation of the altitude control linked to the progressive loss of the gyroscopes. We can then establish that, after correcting for the bias introduced by the different baselines in the two radar pairs, the coherence value left would mainly be affected by the physical changes in the surface.

To estimate the coherence we first made a highly accurate co-registration using precise orbital information, defining a master and a slave image. The resampling of the slave image must be done along range and along azimuth. The oversampling of the two images, master and slave by a factor of 2 is mandatory to generate a high quality interferogram. Then, we applied a filter in the azimuth to avoid the shift caused by the variations in the antenna pointing between the two acquisitions. The azimuth filter used an overlap of 32 pixels. The interferogram computation was done, showing a rather noisy phase that was smooth by averaging adjacent pixels. Coherence maps were generated implementing a multilook filtering too; in fact the phase of the estimated coherence is a filtered version of the original interferogram. Different windows sizes were used in the coherence calculations. The selection of a small window size ensures high spatial resolution, but it can degrade the contrast of the coherence image. We selected two window sizes that could satisfy both requirements, keeping relatively high contrast and high spatial resolution: 5 pixels in azimuth and 1 pixel in the range direction; and 10 pixels in azimuth and 2 pixel in the range direction. This means that the pixel resolution of the resulting coherence images is around 45 meters in the first case, and around 90 meters in the second case (Figs. 3 and 4).

4. RESULTS

Values of coherence in the first pair are generally lower than values in the second coherence pair (see Tab. 2). This is due, in part, to its larger perpendicular baseline (\(\gamma_{base}\)). We calculated the mean coherence image for each pair and for different regions within the Nasca Pampa to see how the coherence values behave and if
some changes were detected between the two scenes. We observed a mean bias of near 0.15 for the whole Nasca area in the two resolutions. For regions, low coherence areas have lower values in the ERS pair than in the ENVISAT pair (see “south” or “crops” classes in Tab. 2); while high coherence areas have higher values on the ENVISAT pairs. If we analyze the data of the table, we realize that none of the regions have a bias higher than 0.23, being the average of all data for the 5x1 resolution of 0.16 and 0.15 for the 10x2 resolution in the desert area. These values are inside the range given by the theoretical Fig. 2. Using the curve in this figure for bare soil (h=0) we have, therefore, corrected the coherence images.

Once the bias introduced by the $\gamma_{\text{base}}$ has been corrected, other decorrelation factors are related to the temporal change of land surface. This is a local temporal decorrelation of the radar reflection characteristics of the surface target between two observations in two different times, and it is related to a temporal change in the ground properties and nature (such as due to changes in snow, vegetation, distribution of scatterers, etc.). These changes can produce speckle variations between the two acquisitions, thus causing a local loss of coherence in an interferometric pair. Large temporal baselines, however, can be used in this is a desert area because loss of coherence related to vegetation is localized (river sides, Fig. 5) and the total amount of vegetation is very low in the whole area [7]. Despite these factors have a minimum effect on our images, still it seems necessary to explain the nature of changes related to a coherency loss. These must be analysed carefully and interpreted with the use of ancillary data. The use of the amplitude images, to see how the backscatter behaves, can be very useful to interpret the results. The amplitude of the return depends on the electromagnetic structure of the target, while the coherence is related to its mechanical stability. Possible factors that causes changes on this dry and flat surfaces are flash flooding and related erosion and deposition; high wind speed that can remove the surface and affecting the drawings; and human activities like road and electric tower construction. Due to the lack of precipitation and the scarce amounts of rain in the near mountains, erosion due to flash flooding is a minimum risk, even if sometimes possible. The annual mean precipitation in the study area and its surroundings only showed a noticeable increase in the Andean area near the Nasca Pampa in 2004 (Fig. 8)[8].

### 4.1. Coherence behaviour by regions

Wind speed rating in the Nasca area is quite high in average; however, wind effects on the flat plain areas do not cause big damages to the lines or geoglyphs due to the nature of the iron-oxide pebbles that cover the sand of the desert. Heavy rains and related flash flooding could cause rapid fluvial erosion/deposition in the area where the gullies dominate. This is the case of the low coherence area that can be observed in the southern part of the Nasca Pampa (“south” class in Tab. 2), near the Nasca river (Fig.6). This area keeps a low coherence in both images, as well as low amplitude values in the four images used. In the optical image we can observe an area surrounded by valleys, probably a badland landscape historically eroded by wind and water. Some Nasca Lines disappeared with the erosion, some still can be slightly seen. Wind can cause some removal of the sand, modifying the scatter response at micro-geometry levels leading to a loss of coherence [9].

Even if we did not detect significant amounts of rain dur-
Table 2. Mean coherence values by regions

<table>
<thead>
<tr>
<th>REGION</th>
<th>ERS5x1</th>
<th>ENV5x1</th>
<th>DIFF5x1 (env-ers)</th>
<th>ERS10x2</th>
<th>ENV10x2</th>
<th>DIFF10x2 (env-ers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CROPS</td>
<td>0.287</td>
<td>0.139</td>
<td>-0.147</td>
<td>0.240</td>
<td>0.050</td>
<td>-0.19</td>
</tr>
<tr>
<td>ROADS</td>
<td>0.745</td>
<td>0.925</td>
<td>0.18</td>
<td>0.807</td>
<td>0.978</td>
<td>0.171</td>
</tr>
<tr>
<td>GULLY</td>
<td>0.669</td>
<td>0.863</td>
<td>0.194</td>
<td>0.718</td>
<td>0.929</td>
<td>0.212</td>
</tr>
<tr>
<td>LINES</td>
<td>0.695</td>
<td>0.928</td>
<td>0.233</td>
<td>0.762</td>
<td>0.965</td>
<td>0.203</td>
</tr>
<tr>
<td>PANAM</td>
<td>0.724</td>
<td>0.669</td>
<td>0.108</td>
<td>0.771</td>
<td>0.880</td>
<td>-0.025</td>
</tr>
<tr>
<td>ALLUV</td>
<td>0.740</td>
<td>0.955</td>
<td>0.215</td>
<td>0.805</td>
<td>0.993</td>
<td>0.189</td>
</tr>
<tr>
<td>SOUTH</td>
<td>0.467</td>
<td>0.462</td>
<td>-0.005</td>
<td>0.510</td>
<td>0.463</td>
<td>-0.047</td>
</tr>
<tr>
<td>IMAGE TOTAL</td>
<td>0.605</td>
<td>0.764</td>
<td>0.159</td>
<td>0.642</td>
<td>0.788</td>
<td>0.146</td>
</tr>
</tbody>
</table>

During the period of study, precipitation seems to be more usual in the Andes piedmont than in the low flat areas (see Fig. 8). In rare occasions this rain is able to arrive to the seasonal rivers that cross the Pampa and it is used in a very efficient way in the riversides. The crops that grow in these areas are able to adapt to the availability of water and time of the year, what makes these regions to change constantly. As a result, coherence values in the river sides are low in both images. There are also some areas of fluvial erosion in these arid lands. They are found in the north-western part of the image. These are regions of badlands and gullies that show a medium-low coherence in the first coherence image (ERS-2), and that are in correspondence with the slopes facing southeast. These slopes are affected by foreshortening effects, what makes them appear very bright in the amplitude images. In the second coherence image these areas show a higher mean value, but still it is possible to see a big difference between the slopes facing southeast and the rest, facing northwest. This loss of coherence is also related to the geometric point of view, as well as the local incidence angle. A variation in the incidence angle is traslated into a frequency shift or discrepancy of the beam’s radar projection on the soil that depends on the orbital distance and the slope of the terrain (Eq. 3).

\[ \Delta F = \frac{F_p \cdot \delta i}{\lg(i - \alpha)} \]  

Where \( F_p \) is the frequency of the radar (ERS=5.3 GHz), \( \delta i \) is the variation in the local incidence angle between the two views, \( \alpha \) is the slope of the terrain and \( i \) the local incidence angle.

The straight lines that are visible in the coherence images are roads. These features are not present in the amplitude images, neither are they clearly visible on the first coherence image. Only the Pan-American Highway is not more than a hint, with lower coherence than its surroundings. The main roads are clearly visible in the second coherence image that shows higher coherence in the flat desert areas with lower coherence values pointing out the main roads and even some smaller ones. The main roads are parallel, crossing the scene from NW to SE, while being crossed by smaller roads and paths, some of them considered to be part of the Nasca Lines. Saubier & Lambers [10] said that the use of geoglyphs included walking along lines; they were paths and roads to easily cross the desert. The Pan-American Highway is an asphalted road, located in the north-eastern part of the scene, whose width is around 10 meters (Fig. 7). The second most important road through the Pampa is located almost in the center of the plateau and has a longitude of more than 20 km and it arrives to 25 m in its wider point. Roads are a result of anthropogenic disturbance, and they are one of the major risks for the preservation of the Nasca Lines. In many places, the trail of the cars turning around in the shoulders of the roads, and the marks of the construction of the electric power towers are destroying and affecting the lines and drawings of Nasca.
5. CONCLUSION

The potential of coherence change detection over the area of Nasca lines has been studied using multi-baseline and multi-temporal SAR images, acquired from ERS-2 and ENVISAT satellites. Coherence products have been analysed and interpreted taking into account local geographic and meteorological features. We found a low bias in the mean coherence value between the two coherence images as shown in Tab. 2. The bias is mainly due to the difference in the perpendicular baseline of each interferometric pair, as well as the different decorrelation factors introduced by the temporal baselines. Main local coherence losses can be related directly to the changes in the surface, mainly due to anthropogenic action (roads, construction, etc.). Only a small part of the changes are related to natural or atmospheric effects (wind and flash flooding). In order to continue with this work, it will be necessary to acquire more interferometric pairs and to compute the coherence in different, recent, time intervals. This will probably allow us to detect additional recent changes in the area and, possibly, to help us make a better normalization of the coherence values (in the discrimination between decorrelation factors coming from temporal changes and those related to other effects). Another important issue in future work would be the use of TerraSAR-X data, a side looking X-band (9.65 GHz) with a stripmap imaging module (1.7-3.5m ground resolution) and an additional spotlight mode (1.48-3.5m in single polarization ground resolution) [11]. This spotlight mode would allow us to compute a coherence map with a higher spatial resolution, adapted to the scale of the single lines, rather than for an average analysis by region as it has been done in the present work.

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REFERENCES

Figure 8. Annual precipitation in SW Peru, GPCC