Física de la Tierra ISSN: 0214-4557
2002, 14, 55-84

SYNTHETIC APERTURE RADAR INTERFEROMETRY (INSAR): APPLICATION TO GROUND DEFORMATION STUDIES FOR VOLCANO AND SEISMIC MONITORING.

R. Romero [1], J. Fernández[1], D. Carrasco[2], F. Luzón[3], A. Martínez[2], G. Rodríguez-Velasco[1], V. Moreno[2], V. Araña[4], A. Aparicio[4]

[1]Instituto de Astronomía y Geodesía (CSIC-UCM), Fac. CC. Matemáticas. Ciudad Universitaria. 28040-Madrid.
[2]Indra Espacio. Departamento de Teledetección. C/ Mar Egeo. San Fernando de Henares. 28850-Madrid.
[3]Departamento de Física Aplicada, Universidad de Almería. Cañada de San Urbano, s/n, 04120-Almería, Spain.
[4]Museo Nacional de Ciencias Naturales (CSIC). José Gutiérrez Abascal, 2. 28006-Madrid.

ABSTRACT

Several applications of InSAR in volcano and seismic areas are described. The aim is to demonstrate the utility of this space technique for routine monitoring in these hazard areas and show that satellite radar interferometry could be routinely integrated in operational volcano monitoring procedures as a complement to other collected data or as a monitoring technique on its own. The scenarios chosen were the Canary Islands (Tenerife, Lanzarote y La Palma) and in a second stage, Ecuador (Tungurahua volcano and Galapagos islands). Results obtained have been very different in every scenario: at Tenerife island we have found two deformations outside the usual monitoring areas and have verified the results of no deformations previously obtained in Las Cañadas Caldera with ground surveys; at Lanzarote and La Palma islands we have not found any deformations greater than 3 cm. Ground deformations have been obtained in Galapagos Islands, due to recent eruptions and no deformation has been found in Tungurahua volcano, despite very recent eruptions. Moreover, seismic studies in South of Iberian Peninsula (Adra earthquake in 1993) have shown displacements, still under consideration.

1. INTRODUCTION

Active volcanoes and seismic areas are closely monitored to try to forecast an eruption or earthquake and, if occurs, to study the phenomenon. There are several instrumentation and geodetic and/or geophysical terrestrial techniques for studying these areas, but all of them have one thing in common, they include point specific measurements. Since 1990's, a new space technique was successfully applied to detect ground deformations, indeed displacements produced by Landers earthquake (Massonnet et al, 1993). This technique, named Synthetic Aperture Radar Interferometry (InSAR) (Zebker et al., 2000; Massonnet and Sigmundsson, 2000; Bürgmann et al., 2000), is based on the use of satellite radar images for obtaining a deformation map of the studied area, and can provide information in a 100 km X 100 km area (size of ERS SAR image).

Since then, InSAR has been used extensively: for detecting displacement produced by earthquakes (Zebker et al., 1994; Wright et al., 2001), eruptions (Massonnet et al., 1995; Lanari et al., 1998; Amelung et al., 2000), water extraction (Amelung et al., 1999), or civil construction (Fruneau and Sarti, 2000). However, in these applications the researchers knew the triggering event, that is to say, they knew what they wanted to study and they used InSAR to detect the produced displacements.

In our research we have used InSAR that way, to detect the displacements produced by the Adra earthquake (December 23, 1993), but our studies basically aim to show that InSAR can be used operationally as a monitoring technique, complementing the traditionally collected monitoring data in volcano and seismic areas or monitoring a remote area on its own. To prove this, we have applied InSAR on Canary Islands and Ecuador (Tungurahua and Galapagos Islands) since 1999, in the frame of DECIDE-VOLCANO Project (funded by European Space Agency) (Carrasco et al., 2000) and SISMOVOL2000 Project (funded by Ministerio de Ciencia y Tecnología) (Fernández et al., 2002b). The results differ widely at each scenario, but in all of them can be concluded that InSAR can be used as a monitoring technique on its own, although, wherever possible, it is better to complement it with other data for a complete monitoring of the whole risk area.

This paper presents a brief description of InSAR basis and the results obtained at the different volcanic and seismic scenarios.

2. SAR INTEFEROMETRY: BASIS

SAR Interferometry (InSAR) is a space technique based on the phase differences from two radar images, acquired by satellite from separate orbits and at different times, to obtain a ground displacement image of the area in question, called interferogram or fringes pattern. This interferogram shows the difference in the radar signal travel path (satellite to ground and back again) between the two image acquisitions. Each interference or fringe shows a 2π change in the wave phase, assigning it a colour scale (blue-green-yellow-red) or grey scale. If we assume that the two orbits are coincident (zero baseline), the interferogram should be zero flat if the land remains unchanged. Should any displacement occur over the scenario between the two image acquisitions, an additional distance would appear in the radar signal travel path, resulting in a phase component that can be measured precisely. For the ERS satellites, a change in the line of sight distance of 2.8 cm results in an approximate full 2π phase, and thus a fringe in the interferogram. Thus centimetric ground deformations can be measured with InSAR (Massonnet and Feigl, 1998). However, the orbit distance (baseline) is never zero (because satellites follow different orbits in each pass over the same area), so the interferogram reflects this distance as fringes, which are called topographic fringes. Therefore an interferogram contains topographic and deformation fringes. If we are interested in deformation, topographic fringes must be removed (Figure 1), using one of three methods: short baseline (Goldstein et al., 1993), three pass method (Zebker et al., 1994), and two pass method (Massonnet et al., 1993). In our work, we used the last method, which requires using a Digital Elevation Model (DEM) to remove the topographic fringes. Thus, the interferogram obtained (without topography) only shows deformation fringes, and is called a differential interferogram.

The high level of accuracy, along with the large area imaged with each ERS SAR image (100 km^2), are two reasons for using InSAR for geodetic monitoring. ERS-1 was launched by the European Space Agency in 1991 and the first InSAR application for detection of ground deformations in 1993 appeared. Massonnet et al. (1993) used ERS-1 SAR images to detect displacements produced by Landers earthquake (Mojave desert-California-USA) in 1992. The results were amazing, so this technique has been used extensively since then for large applications in ground deformations: co-seisms and post-seisms displacements (Massonnet et al., 1994, 1996; Ozawa et al., 1997; Tobita et al., 1998; Michel et al., 1999; Pollitz et al., 2000; Wright et al., 2001), determination of ice-flow velocity of glaciers (Goldstein et al., 1993; Joughin et al., 1996; Joughin et al., 1998), studies of subsidences produced by human-activities (mining ground water, oil, gas, or minerals; tunnels construction) (Carnec et al., 1996; Massonnet et al., 1997; Fielding et al., 1998; Galloway et al., 1998; Amelung et al., 1999), detection of displacements in volcanic areas (Massonnet et al., 1995; Lanari et al., 1998; Avallone et al., 1999; Beauducel et al., 2000; Amelung et al., 2000).

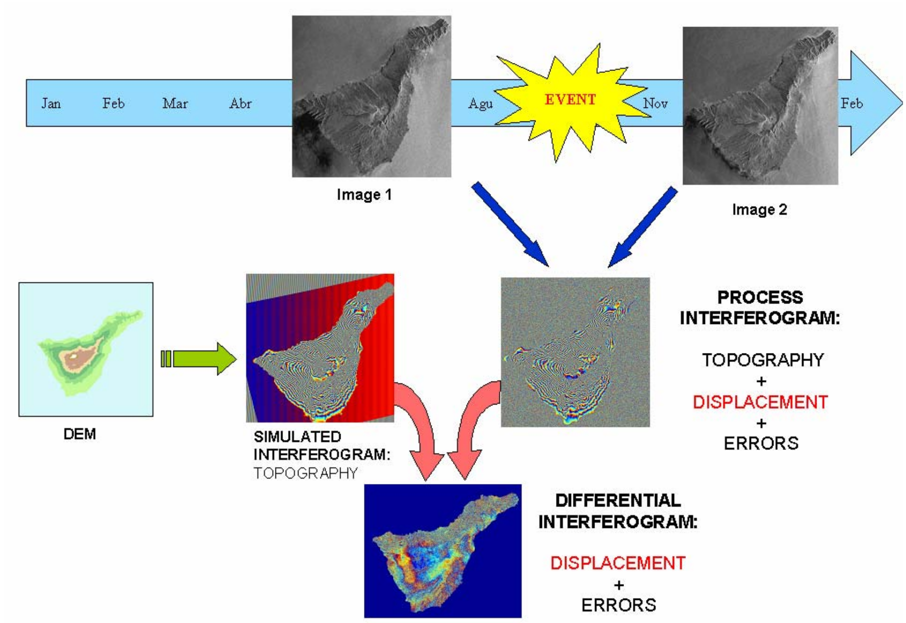

Figure 1. This diagram shows how a differential interferogram is obtained. First, a process interferogram is calculated from two SAR images. This interferogram shows topographic and deformation fringes, and the latter are obtained by using a Digital Elevation Model (DEM), which provides a simulated interferogram that only contains topographic fringes. Next, the topographic fringes are removed from the process interferogram, and a differential interferogram is obtained. Although errors (overall, with atmospheric origin) may appear throughout the process, they can be minimized by studying several differential interferograms.

Nonetheless, this technique has several limitations. One of them is that, like any space technique, the SAR signal is damaged by atmosphere in the sense that the number of wavelengths will change when the signal passes through it, producing a change in the satellite to ground distance known as atmospheric delay. This effect can mask the actual distance between satellite and ground, producing an additional number of fringes in the interferogram that can be interpreted as deformation fringes (Massonnet et al. 1994, Goldstein 1995). There are several ways of distinguishing between atmospheric or deformation fringes and of trying to minimize that atmospheric effect (Zebker et al. 1997; Williams et al. 1998; Beauducel et al. 2000; Romero et al. 2003), but no single way to remove it completely.

Other important limitation is maintaining phase coherence in the area under study. Coherence measures the pixel-to-pixel resemblance between radar images, to assure the stability of ground backscattering over time (Massonnet and Feigl, 1998; Bürgmann et al., 2000; Hanssen 2001). Changes over terrestrial surface (ground moisture changes, landscape erosion, crop growing), movement of the leaves in the trees, the changing surface of the sea, etc. produce a variation in the backscattering, adding noise in the phase differences, so it is difficult to obtain fringes in the interferogram. Areas with scarce or null vegetation are the best for obtaining “good coherence” (good quality phase) and so, a good quality interferogram.

Furthermore, differential interferograms only show deformation in the satellite line of sight, so only one component of displacement is seen. It is possible to obtain two components by using ascending and descending passes but, with current satellites, the three components are only obtained if something characteristic about displacement is known, like for glaciers, where it is supposed that they are parallel to surface (Joughin et al., 1998).

Due to these advantages and drawbacks, InSAR can only be used in certain areas. Several aspects have to be studied before this technique is applied, taking into account how we want to use InSAR, for monitoring a risk area (several years research) or if we want to study a specific past event (earthquake, volcano deformation after an eruption, etc). In both cases, good coherence is essential, but this can may more critical in the first case, when more images are involved. It is essential to have information about vegetation (absence or presence, type of soil, ...), weather (dry, rainy, less changing seasons, ...), direction and magnitude of possible deformation, etc., for a good selection of the SAR images. Furthermore, for monitoring it is necessary to cover a large time (for example, from 1991 to 2001 when the ERS satellites were available for interferometry) with a homogeneous distribution of images during that time.

3. APPLICATION TO GROUND DEFORMATION STUDIES ON VOLCANIC AREAS.

Our volcanic studies have focused on the Canary Islands (Tenerife, Lanzarote and La Palma), Galapagos Islands and Tungurahua volcano

(Ecuador). The Canary Islands were selected because are the only active volcanic area in Spain. The last eruption dates from 1971, in the Teneguía volcano (La Palma), so a more active scenario was required to prove that InSAR might be useful for trying to detect an eruption and monitoring a remote area, such as the Galapagos and Tungurahua volcano in Ecuador.

3.1. CANARY ISLANDS

This archipelago is located between 27º and 30º latitude N and 13º and 19º longitude W (Figure 2) and its volcanic activity began 40 m. y. ago (Araña and Ortiz, 1991). We choose Tenerife, Lanzarote and La Palma as scenarios to apply InSAR because a dozen eruptions have occurred there over the last 500 years (Tenerife: 1704, 1706, 1798, 1909; Lanzarote: 1730-36, 1824; La Palma: 1585, 1646, 1677, 1712, 1949, 1971) (see e.g., Felpeto et al., 2001), and therefore any eruption in the future is more likely to occur on these islands than on the others.

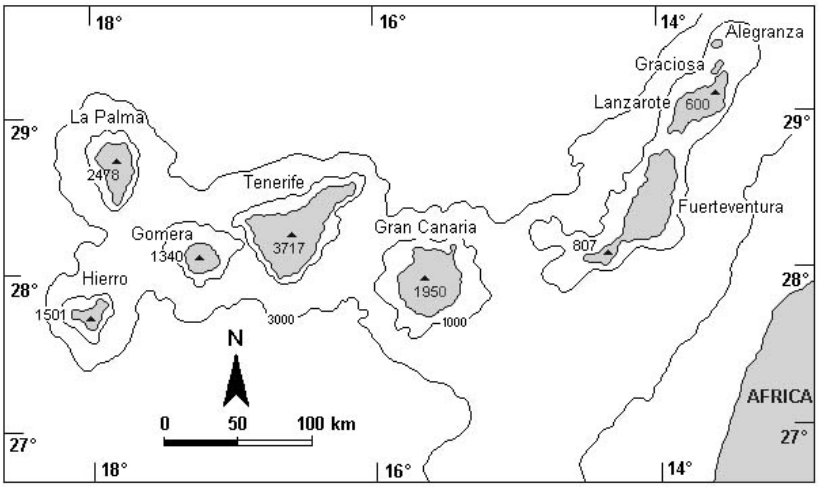

Figure 2. Canary Islands site.

Tenerife

Tenerife is the largest island in the Canaries. Most recent volcanic activity is associated to monogenetic volcanoes that are aligned on two volcanotectonic axes: NW-SE and NE-SW, forming the recent ridges: NW-SE ridge and NE-SW ridge (Figure 3, upper box). These two ridges are linked in the centre of the island by Las Cañadas Caldera, an elliptical depression measuring 16x9 km^2 which was built when Las Cañadas volcano collapsed 0.2 m. y. ago (Ancochea et al., 1990). In the north of this caldera is the Teide-Pico Viejo complex, a double stratovolcano that is still active, although its activity is limited to fumaroles in the summit of Teide volcano (Araña et al., 2000a).

Geodetic monitoring on the island prior to our research focused on Las Cañadas with a geodetic and a levelling network located in the south of the Caldera (Sevilla and Romero, 1991), which were built to detect displacements associated to volcanic activity inside the networks. Both of them have been periodically reobserved since being installed in 1987. Furthermore, gravimetric campaigns have been conducted to study the three-dimensional structure of the island (Vieira et al., 1986; Ablay and Kearey, 2000; Araña et al., 2000b), and temperature and concentrated gas monitoring in the summit of Teide (Salazar et al., 2000). However, none of the observations performed to date in the Caldera have indicated any anomaly that might point to volcanic unrest in this area. Outside the caldera, there is a geodetic network (covering the whole island) marked and observed by the Instituto Geográfico Nacional (IGN) using GPS in 1994 (Blanco et al., 2000), and there are also IGN seismic stations for controlling earthquakes with a magnitude greater than 2.5 (Blanco et al., 2000).

Thus, despite the nature of volcanism on Tenerife (there has not been more than one eruption in the same volcanic edifice, except for the Teide and Pico Viejo volcanoes) and the location of the last eruptions on recent ridges, the monitoring focused on a small area, Las Cañadas Caldera.

In accordance with its volcanism, the last eruptions and the theoretical results obtained by Yu et al. (2000), the best monitoring system would have to cover the whole island. Therefore InSAR was used, since one SAR image covers the whole island.

For Tenerife we used 18 SAR images, taken by the European Space Agency satellites ERS-1 and ERS-2 during the period 1992-2000. Theses images were processed with EPSIE2000 software (Martínez and Moreno, 1997), giving 21 differential interferograms. Good coherence was obtained (Figure 4), even for time-spans beyond 7 years, due to the fact that much of the island has not been covered yet by vegetation (Las Cañadas Caldera and the areas of the last eruptions). Therefore InSAR can be applied on Tenerife for routine monitoring.

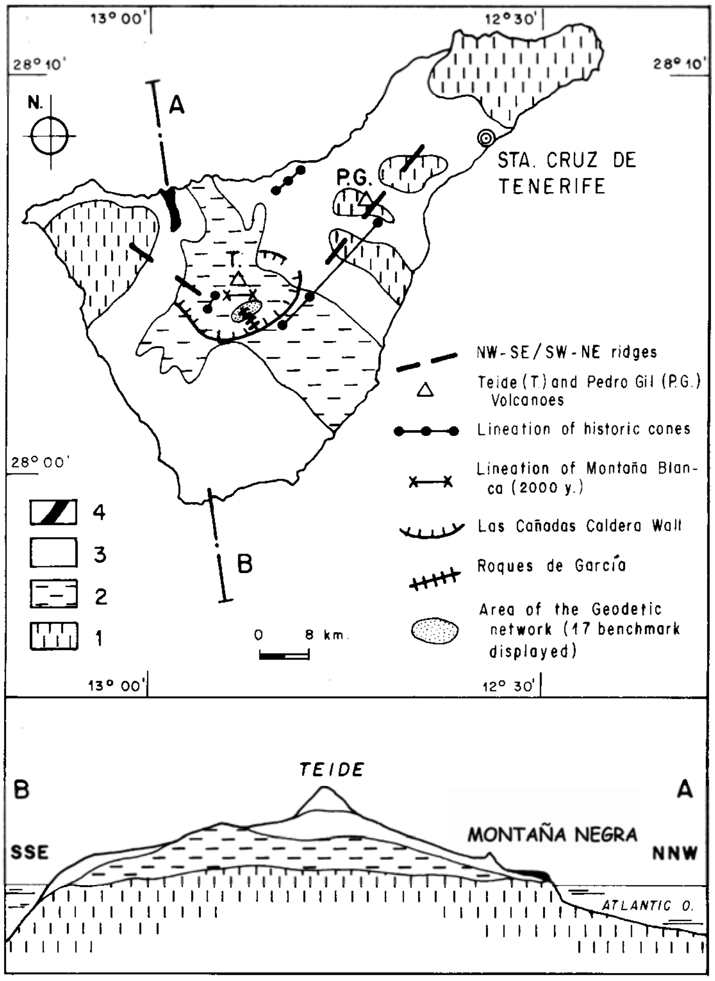

Figure 3. Geographical and geological information. In upper box, geological sketch of Tenerife Island: 1-Ancient basaltic series, 2-Cañadas series, 3-Recent and historical series, and 4-1706 Montaña Negra eruption lava flows. It also shows the location of Tenerife ridges, and geodetic network. Roques de García is a spur between the two calderas. Lower box, geological section (A-B) also showing the position of Teide complex and Montaña Negra volcano. Positive latitude to the N and positive longitude to the W in the figure (modified from Fernandez et al., 2002a).

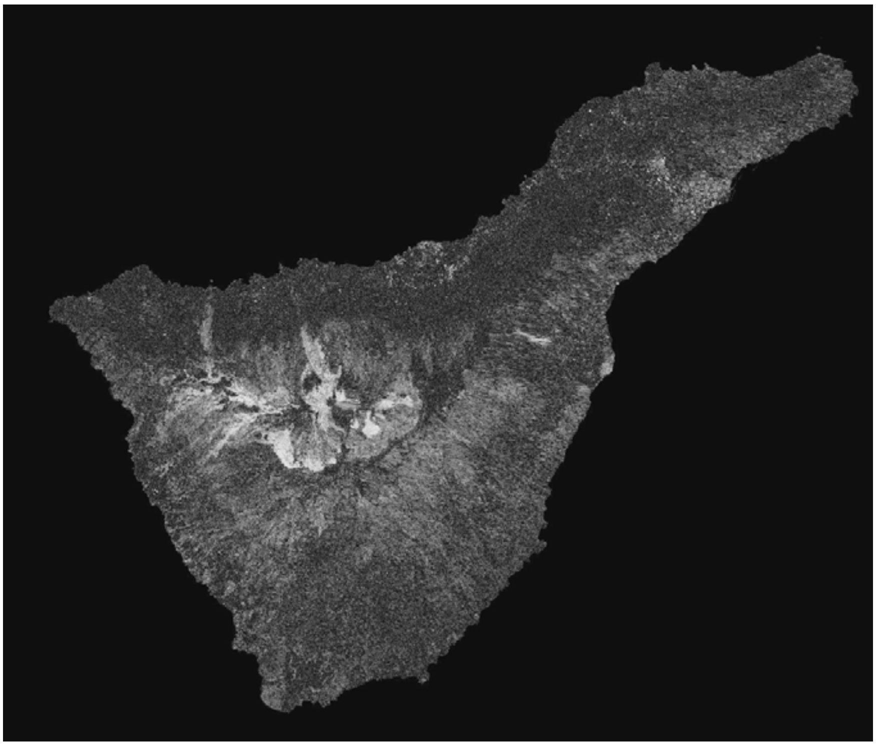

Figure 4. Coherence image from Tenerife island for 2agu96-15sep00. Best coherence (white) can be seen at Las Cañadas Caldera and at NW-SE ridge, the area of the last eruptions.

Moreover, two important results were obtained: a) no deformation in Las Cañadas Caldera, coinciding with terrestrial techniques (Figure 5), and b) two land subsidences outside the monitored areas in the NW of the island, where the last eruptions occurred. These deformations have been named Garachico (Figure 5.a) and Chío (Figure 5.b), respectively. Both of them are subsidences that increased from 1992 to 2000. The Garachico deformation measured about 9 cm between 1993-2000, covering 15 km² and is located at Montaña Negra volcano lava flows, one of the last historic eruptions (1706)on the island. The Chío deformation measured about 3 cm between 1993-2000, extends over 8 km² on the south of Garachico deformation and is also an area covered by basaltic material (which is the reason for the good coherence).

To check these deformations and monitor the areas lacking coherence (i.e., where no InSAR information is available), we designed a GPS network (using vertexes built by IGN whose coordinates are determined in the REGCAN-95 geodetic system (Caturla, 1996)) that covered the whole island and was densified in the north-western deformation area . Both networks were first observed in 2000 (Rodriguez-Velasco et al., 2002; Fernandez et al, 2002a).

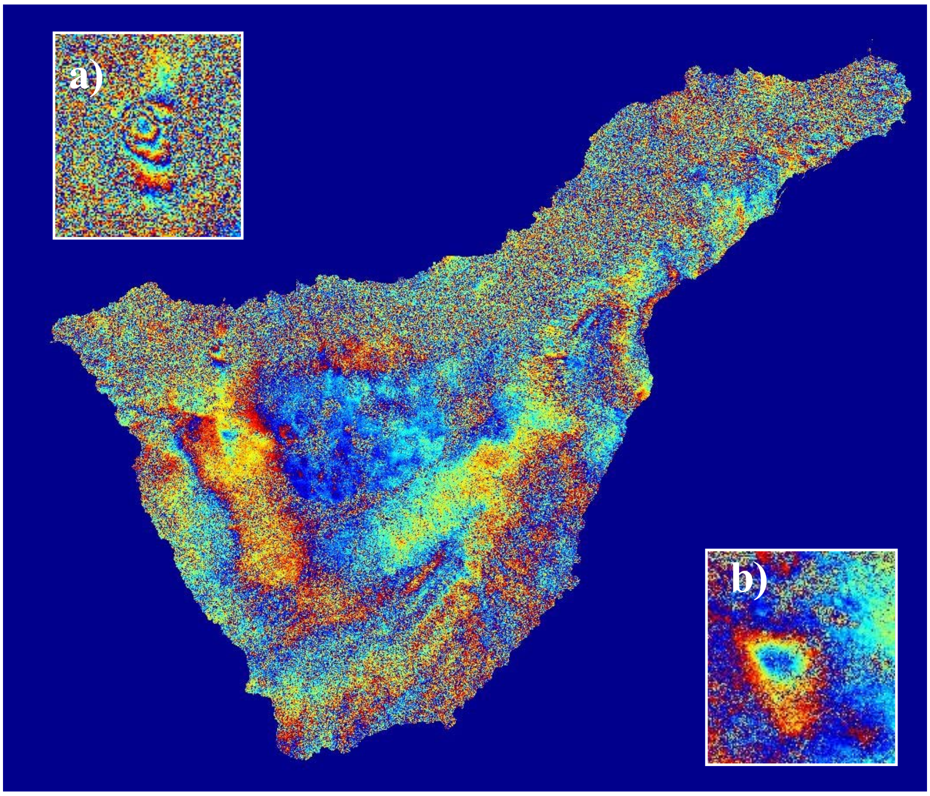

Figure 5. Differential interferogram from Tenerife island for 2agu96-15sep00. No fringe can be seen in the Las Cañadas area, so there is no deformation from 2agu96 to 15sep00. a) and b) are Garachico and Chío subsidences, respectively, from 20jul93-15sep00 differential interferogram. At Garachico subsidence there are 3 fringes, i.e., ≈ 9 cm of ground subsidence from 20jul93 to 15sep00; at Chío subsidence there is 1 fringe, i.e., ≈3 cm of ground subsidence from 20jul93 to 15sep00.

The results from these campaigns confirmed the Chío deformation and revealed other points of deformation in the north of the island, in non-coherent areas. Therefore the two techniques complement one another, with the GPS data making up for the lack of information from InSAR.

Lanzarote

Although there have only been two historic eruptions on Lanzarote (1730-36, 1824), they have been two of the most important eruptions in the Canaries. Indeed, the 1730-36 eruption was one of the biggest basaltic volcanic events ever seen by man (Araña, 1997). During this event, known as the Timanfaya eruption, 1 km^3 of lava was emitted from different mouths aligned in a fracture 14 km long, covering an area approximately of 200 km^2 (Felpeto et al., 2001) and forming Timanfaya National Park (Figure 6). Nowadays, there are still geothermal and seismic anomalies due to 1730-36 eruption in this area (Romero et al., 2003).

The clear likelihood of future activity, together with the island's structural and geodynamic characteristics, prompted the installation of a permanent Geodynamic Laboratory in 1987 (Vieira et al., 1991; Fernández et al., 1992). Several instruments have been set up in this station in these years, permitting ongoing observation of deformation, gravity changes, sea level, temperature inside rock and different meteorological parameters. According to the collected data, no deformation or gravity change related to volcanic activity has been detected between 1987 and 2000 (Arnoso et al., 2001).

However, the volcano monitoring system installed on Lanzarote only supplies information from 2 areas: Cueva de los Verdes and Timanfaya National Park (see location in Figure 6). This poses two problems: there is no information about the deformation field of whole island and, in case of volcanic unrest, it would be very difficult to infer information about the intrusion characteristics. Consequently we thought that it would be better to use a technique to monitor the whole island, such as InSAR, like on Tenerife.

For Lanzarote we used 6 SAR images, taken by the ERS-1 and ERS-2 satellites during the period 1992-2000. Good coherence was obtained in most interferograms, principally in Timanfaya National Park and Corona volcano area (Figure 7), so InSAR can be used for routine monitoring of volcanic activity on this island. Different atmospheric artefacts were found in most interferograms, but we managed to separate them from the other interferometric signal (Romero et al., 2003). Consequently, we can assure that on Lanzarote island there is no deformation greater than 3 cm of vertical ground deformation (Figure 8), coinciding with the Geodynamic Laboratory results.

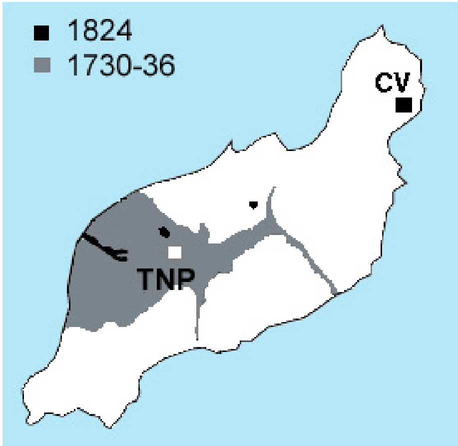

Figure 6. Geological sketch of Lanzarote island, showing the two historic eruptions, Timanfaya eruption (1730-36) and 1824 ones. TNP (Timanfaya National Park) and CV (Cueva de los Verdes) mark the instrumentation location of Geodynamic Laboratory (modified from Romero et al., 2003).

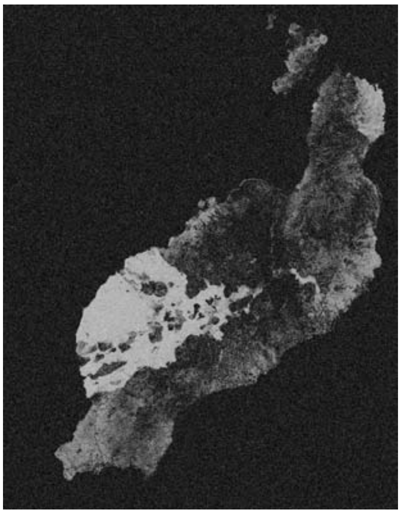

Figure 7. Coherence image from Lanzarote island for 11agu95-16agu97. Areas of best coherence (white) are Timanfaya National Park (southwest) and La Corona volcano (northeast), where Geodynamic Laboratory instrumentation has been installed (see Figure 6).

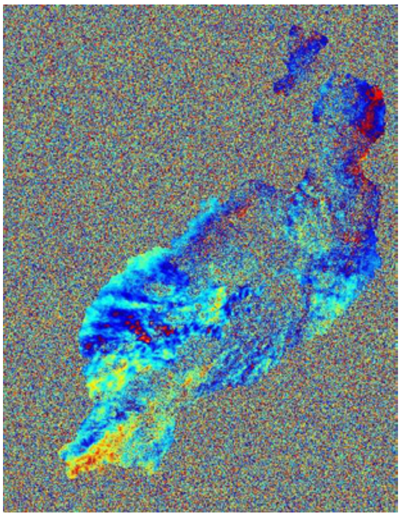

Figure 8. Differential interferogram of Lanzarote island for 11agu95-16agu97. There is no deformation fringe anywhere on the island. The artefacts are of atmospheric origin.

La Palma

La Palma accounts for most of the eruptions that have occurred in the archipelago over the last 500 years (historic eruptions), and all the eruptions on this island have taken place at the Cumbre Vieja ridge, to the south of the island (Romero, 2000). Indeed, the last eruption in the Canary Islands occurred at Teneguía volcano in 1971, which is why La Palma has become one of the most closely monitored islands of the Canaries in recent years. In 2000 and 2001, this island became very famous among scientists following the publication of several articles (Moss et al., 1999; Day et al., 1999; Ward and Day, 2001) which warned that a landslide might occur on the southern part of the island in the event of a new eruption, although not all scientific researchers agree with this (Araña, 2000).

Since 1994, the Cumbre Vieja ridge and the west flank, where the last eruptions occurred, have been monitored by geodetic network. The results obtained in the campaigns carried out are within the error-margins of the techniques employed (Moss et al., 1999). Like in Tenerife and Lanzarote, the whole island is covered by an IGN-owned GPS network, observed once in 1994, and seismic stations.

Therefore, and again like Tenerife and Lanzarote, there is no monitoring system designed to cover the whole island, which is why we considered using InSAR to detect any deformation. For La Palma we used 6 SAR images, taken by the ERS-1 and ERS-2 satellites during the period 1992-2000, but we did not have DEM to remove the topography in the interferograms. However, due to the short baselines (less than 20 m) between images, we can assure that there is no deformation greater than 3 or 4 fringes (9-12 cm ground displacement) on this island, although small deformations might be masked by topographic fringes. These results match terrestrial techniques. The coherence obtained has been good, although a large part of La Palma island is covered by abundant vegetation. Areas of higher coherence correspond to recent lava fields of the last eruptions that occurred on the island (Figure 9) and are located in the southern part and in areas close to Taburiente Caldera.

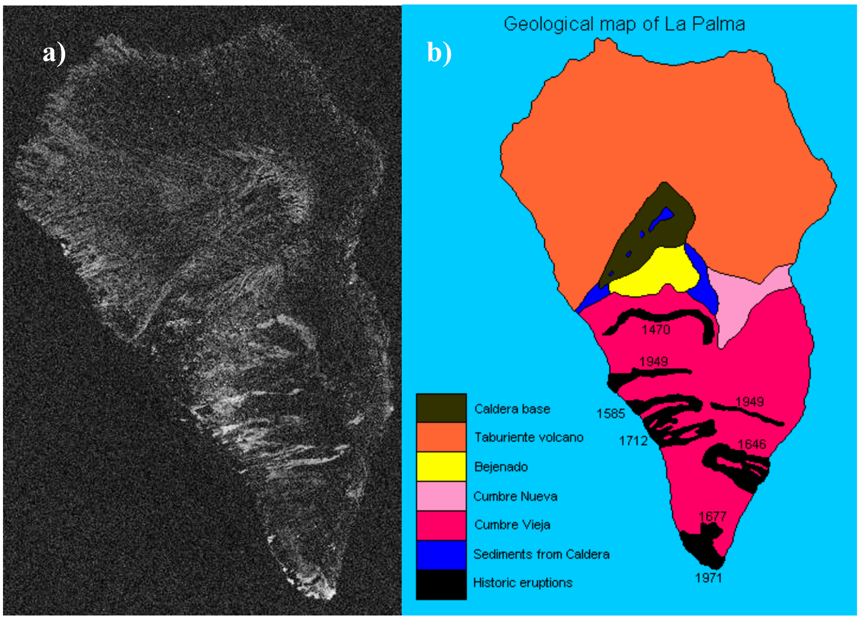

Figure 9. a) Coherence image of La Palma island for 10oct93-20agu95 and **b)** geological map of La Palma. Areas of higher coherence (white) in a) coincide with lava flows of the last eruptions that occurred on the island, according to **b)**. Geometric deformation in **a)** with respect to **b)** is due to stretching by ERS satellites.

This is the first time that InSAR has been applied in the Canary Islands for volcano monitoring purposes, in the sense that we have used images covering many years. Massonnet and Sigmundsson (2000) show one interferogram of La Palma island that covers the period 1992-1995, but without removing the topography as we have. In the light of this interferogram, the authors reach the same conclusions as us, namely that no deformation has occurred, although they suggest that more images are required to identify the timing of changes in a volcano, as we have done. However, we also have to remove the topographic fringes to assure that they do not mask deformation. Later, especially if any deformation is found, this island would be a good scenario for using InSAR and GPS together, because the coherence is not good enough in hazard areas (Cumbre Vieja ridge), where a geodetic network has been installed (Moss et al., 1999). This network could be used together with the IGN network in the same way as on Tenerife (Fernandez et al., 2002a).

3.2. ECUADOR

Although the Canary Islands are an excellent scenario for using InSAR to monitor a volcanic area, as we have seen, there have not been any eruptions or major activity in the last few decades. Consequently, we decided to apply InSAR to Ecuador in order to select a more active area with recent eruptions such as Tungurahua volcano and Galapagos Islands, where InSAR could be tested in a similar way as in the Canaries. The deformation associated to the most recent volcanic activity in Galapagos Islands and its detection using InSAR technique has been described in several papers (see for example; Jönsson et al., 1999; Amelung et al., 2000). Like the Canaries, they are an excellent scenario due to volcanic origin and absence of vegetation, allowing a very good coherence and thus clear detection of the displacements that occurred during volcanic activity in the 1990's. Tungurahua is one of the Ecuador's most active volcanoes, and has erupted several times in recent years (1999, 2000 and 2001).

Galapagos Islands

The Galapagos Islands consist of at least 20 basaltic hotspot volcanoes grouped in several islands, located 1000 km to the west of Ecuador mainland, in the Pacific Ocean (Figure 10). Two different types of volcanoes are to be found in the Galapagos. In the west, on the Isabela and Fernandina islands, large volcanoes with an "inverted soup-bowl" morphology and deep calderas occur (Simkin and Howard, 1970; Chadwick and Howard, 1991). These volcanoes are among the most active in the world (Simkin, 1984). In the east,

a)

b)

Figure 10. a) Galapagos islands and Tungurahua volcano location and **b)** a more detailed map of Galapagos.

smaller shield volcanoes with gentler slopes occur. Our research focused on Fernandina and Isabela islands, specifically on the Fernandina, Cerro Azul, Sierra Negra and Alcedo volcanoes. Eruptions have occurred in all of them in the last century, the 1995 Fernandina eruption and 1998 Cerro Azul eruption being the most recent ones (Amelung et al., 2000).

Volcano monitoring on Galapagos is not an easy task. The archipelago is a long way from the mainland (1000 km) and field work is expensive. Despite being a first class natural scenario, the islands' small population (even including the restricted tourism) make it less important than the mainland, in terms of volcanic risk. Nevertheless, until 1990 there was a World Wide Standardized Seismic Network (WWSSN) station for registering events larger than magnitude 4.0 Richter and in 1997 the Instituto Geofísico de Ecuador deployed a seismic network for monitoring events of magnitudes down to 2.0 Richter (but this network has not been working continuously). Therefore the Galapagos Islands is a good scenario for proving that InSAR can be used as a monitoring technique in a remote volcanic area, due to its recent activity and the scarce monitoring.

5 differential interferograms were obtained with 8 SAR images, taken by ERS-1 and ERS-2 satellites, from 1992 to 2000. Coherence in Galapagos Islands is excellent, due to their volcanic origin. There are two areas of low coherence, due to dense vegetation: the south (south of Cerro Azul and Sierra Negra volcanoes) and central part (Alcedo volcano) of Isabela island (Figure 11).

Deformations were detected at the four volcanoes: Fernadina, Cerro Azul, Sierra Negra and Alcedo. Our results are very similar to Amelung et al. (2000) ones. They used images from 1992 to 1999, whereas we used images from 2000 (May00 and Jun00). Apart from detecting the same deformations for the same time span, our study also revealed a new deformation in Fernandina volcano and a subsidence in Alcedo volcano caldera. The DEM used for removing topographic fringes had large errors in the south of Isabela island, so the differential interferograms of this area have topographic fringes, preventing us from calculating the exact magnitude of certain deformations. The bottom of the calderas is flat, so the displacement inside them did not need DEM correction. The results obtained at the four volcanoes are given below.

Fernandina

Two ground subsidences of about 3 cm were detected in the northern part of volcano (corroborating the results of Amelung et al., (2000)), and in the lava flows of 1995 eruption, during the period Oct98-Jun00 (Figure 12.1.), not detected by Amelung et al. (2000). Furthermore, a lava flow subsidence was detected on the south-eastern part of the island (coinciding with Amelung et al. (2000)), with a magnitude of 3-6 cm in Jun92-Nov98 interferogram (Figure 12.2.).

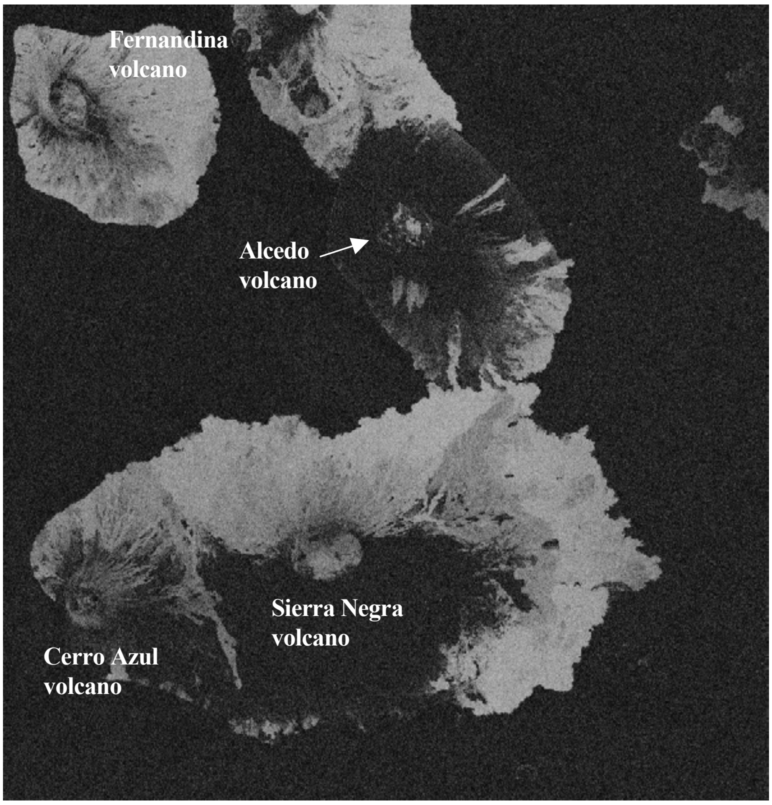

Figure 11. Coherence image for Oct98-Mar99 interferogram. In white, coherent areas and in black, non-coherent areas (inland black zones coincide with vegetation areas).

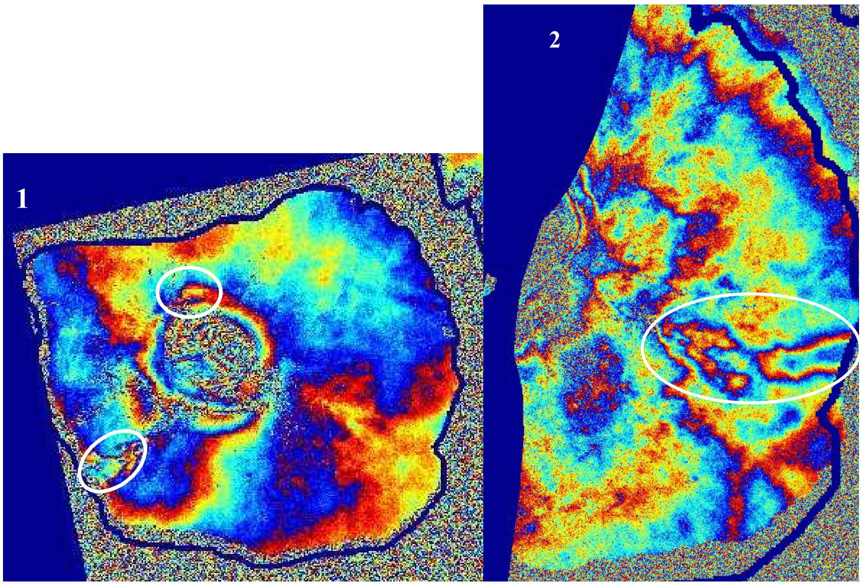

Figure 12. 1) Fernandina island interferogram for Oct98-Jun00. In white circles, Fernandina subsidences. **2)** Fernandina island (eastern area) interferogram for Jun92-Nov98. In white circle, lava flows subsidence.

Cerro Azul

Subsidence was detected in the north-eastern part of the summit, associated to the Sep-Oct98 eruption, although it is not located in that area. This subsidence is only visible in the Jun92-Nov98 interferogram (Figure 13), but is masked by topographic fringes that could not be removed with DEM, so its magnitude cannot be obtained.

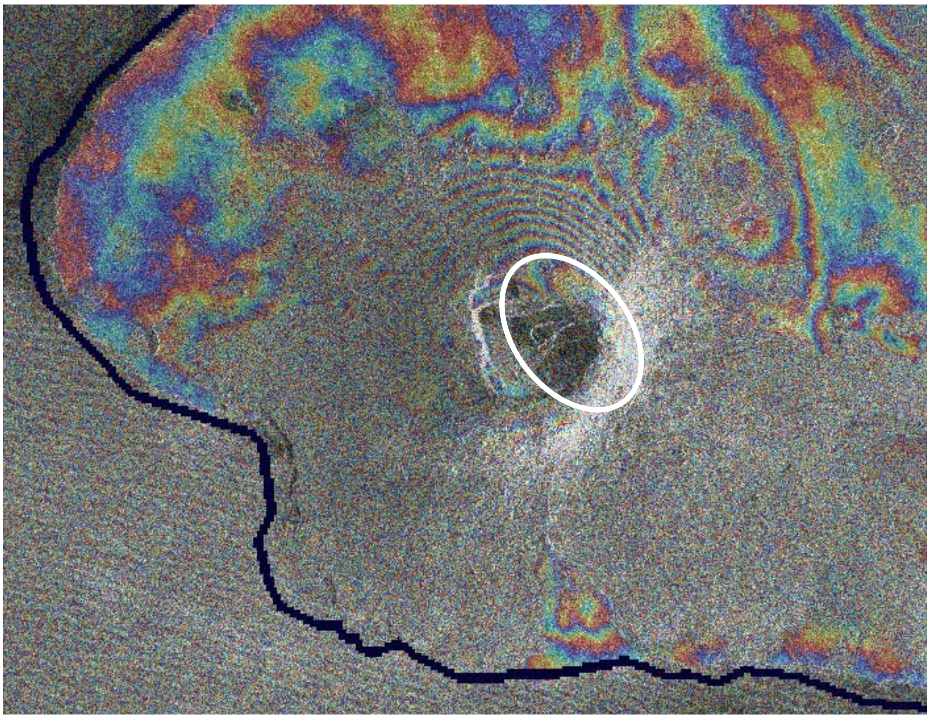

Figure 13. Jun92-Nov98 interferogram overlaid amplitude image, for the Cerro Azul volcano. Fringes are visible around the volcano and in the north-eastern part of thesummit. The former are topographic fringes and latter (white circle) are subsidence.

Sierra Negra

An uplift was detected inside the caldera, corroborating the results of Amelung et al. (2000). The uplift measured about 207-210 cm in Jun92-Nov98 interferogram (Figure 14), but is decreasing, because in the Mar99-Jun00 interferogram it only measured about 6-9 cm.

Like Amelung et al. (2000), we detected a lava flow subsidence in the north of the Sierra Negra volcano, in an area of former lava flows. The magnitude of the subsidence could not be obtained because these fringes were mixed with topographic fringes that could not be removed with DEM (due to the DEM error mentioned earlier). This deformation is not so clear in other interferograms.

The deformation found in the Sierra Negra volcano in recent years confirms the information from fieldwork about severe cracks and ground deformation.

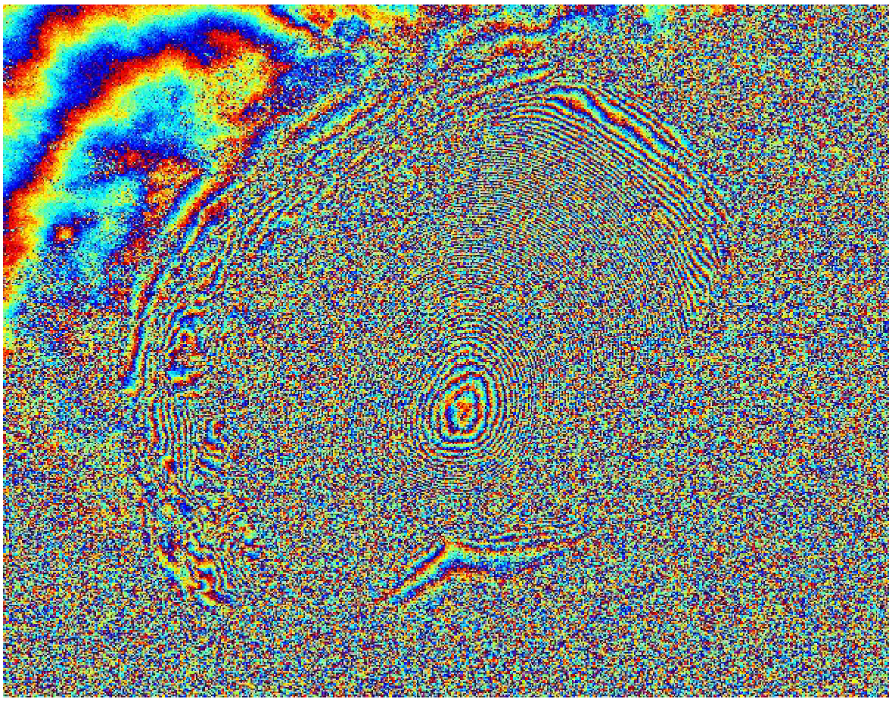

Figure 14. Jun92-Nov98 interferogram for Sierra Negra volcano caldera. There are 71 fringes, two of them are due to topography and the rest is an uplift of about 2 m.

Alcedo

The Jun92-Nov98 interferogram (Figure 15.1.) revealed deformation inside the caldera, in the form of an uplift of about 72-81 cm, (coinciding with Amelung et al. (2000)) whereas the Oct98-Jun00 interferogram (Figure 15.2.) revealed a subsidence of about 6 cm. This subsidence has been observed in 3 differential interferograms, showing that it is not an atmospheric artefact.

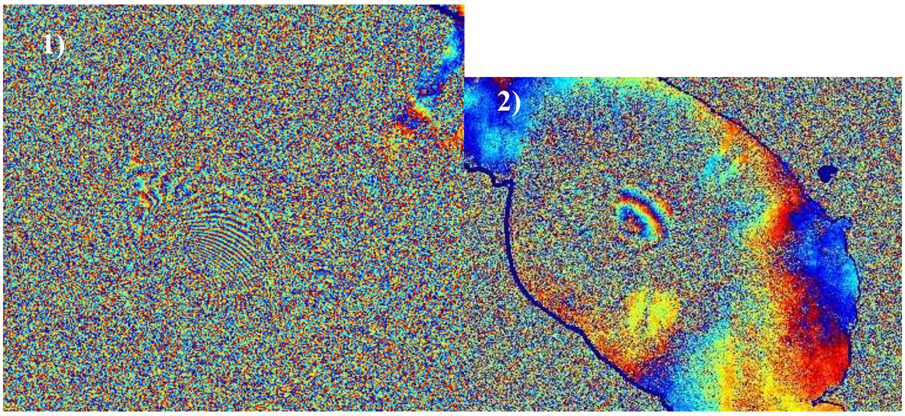

Figure 15. 1) Jun92-nov98 interferogram of Alcedo volcano. Fringes are only visible inside caldera, the rest is incoherent due to vegetation in this area. This fringes show an uplift of about 72-81 cm. **2)** Oct98-Jun00 interferogram of Alcedo volcano. Two fringes inside caldera show a subsidence of about 6 cm.

Tungurahua volcano

Tungurahua is one of Ecuador's most active volcanoes, with an elevation of 5023 m (Hall et al., 1999). It is located 120 km south of Quito, although the nearest city is Baños, 9 km northeast of Tungurahua's summit (Figure 10). Historical eruptions (1534, 1557, 1640, 1641, 1644, 1646, 1757, 1773, 1776, 1777, 1857, 1885, 1886-88, 1900, 1916-25, 1944, 2000, 2001) have originated from the summit crater and have included strong explosions and sometimes lava flows, lahars, and pyroclastic flows that reached populated areas at the volcano's base.

The Instituto Geofísico runs a permanent monitoring station near the volcano where they record data (through radio telemetry) from field deployed seismometers and microphones in the volcano flanks. Additionally, there is a monumented Electronic Distance Measurement (EDM) network for the measuring of ground displacement. This instrumentation is located in the northwest area of the volcano (Tungurahua young edifice) (Hall et al., 1999), where the last eruptions occurred, having registered the volcanic activity in the last years (1994, 1998, 1999, 2000 and 2001). The availability of satellite data (InSAR) provided a unique tool not only for the monitoring of the volcano, but to assess the instrumentation results, which had not been cross-checked until now.

11 ERS SAR images (acquired by ERS-1 and ERS-2 satellites from 1992 to 2000) were used to obtain 13 interferograms. The images were chosen to try to detect any deformation between periods of activity of Tungurahua volcano in 1994, 1998 and 1999. In general, Tungurahua volcano shows good coherence with short temporal separation and baseline, but due to frequent volcanic activity in recent years (ash emission and lahars) and long temporal separation, the ground properties change, and the coherence is very poor, as after ash clouds. Tungurahua's summit (the last 100 m) does not show good coherence due to snow. The images with good coherence show the volcano as a ring (Figure 16.1.). The inner area is incoherent (snow), as is the outer area because the green landscape is covered in vegetation. The main part of the cone is coherent because it is not covered with vegetation or snow. Therefore all the interferograms only show a small area of Tungurahua volcano (about 1000 m high), where we have not found any clear deformation. There is only a ½ fringe of deformation between Jul98 and Jan99, which has not been not confirmed with additional data (Figure 16.2.).

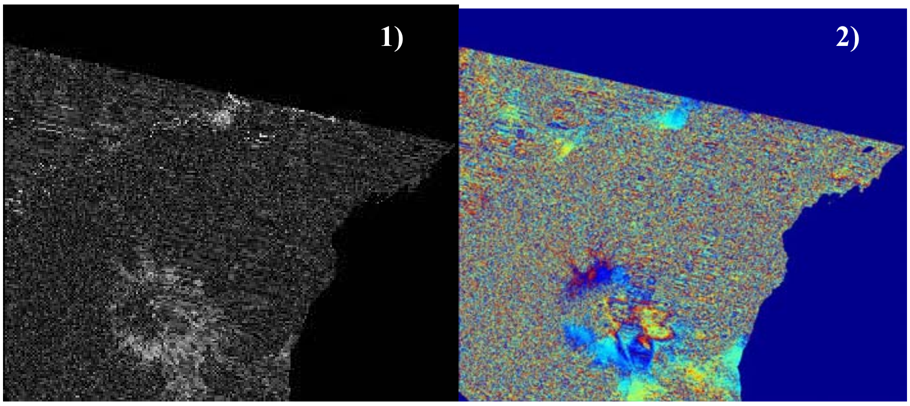

Figure 16: Coherence image (1) and interferogram (2) for 31jul98-22jan99. Good coherence visible on flanks of Tungurahua. Summit has no coherence due to snow. In white circle ½ fringe of deformation.

4. APPLICATION TO GROUND DEFORMATIONS STUDIES ON SEISMIC AREAS: ADRA EARTHQUAKE

Southern Spain has the highest level of seismic hazards of all Spanish regions, as observed in historic earthquakes (Buforn et al., 1995) and in the instrumental seismic records kept by the Andalusian Institute of Geophysics and the National Geographic Institute.

On December 23, 1993 an earthquake of magnitude Mb = 5.0 occurred between the towns of Adra and Berja (South Spain) at 14:22:34.5 (U.T.) (Figure 17). This earthquake was felt extensively in Spain, causing some damage in the epicentral zone with a maximum intensity of VII (M.S.K.) (Martínez Solares and Pascual, 1996; Rueda et al., 1996). A few days later, on January 4, 1994, another earthquake of magnitude Mb = 4.9 occurred 26 km to the southeast of the first one, in the Alborán Sea. This one was also felt in a large part of Spain, and also reached a maximum intensity of VII (M.S.K.) in areas near the epicentre on the Spanish coast (Martínez Solares and Pascual, 1996; Rueda et al., 1996). These two principal earthquakes were followed by a long seismic series of small earthquakes that last more than a year.

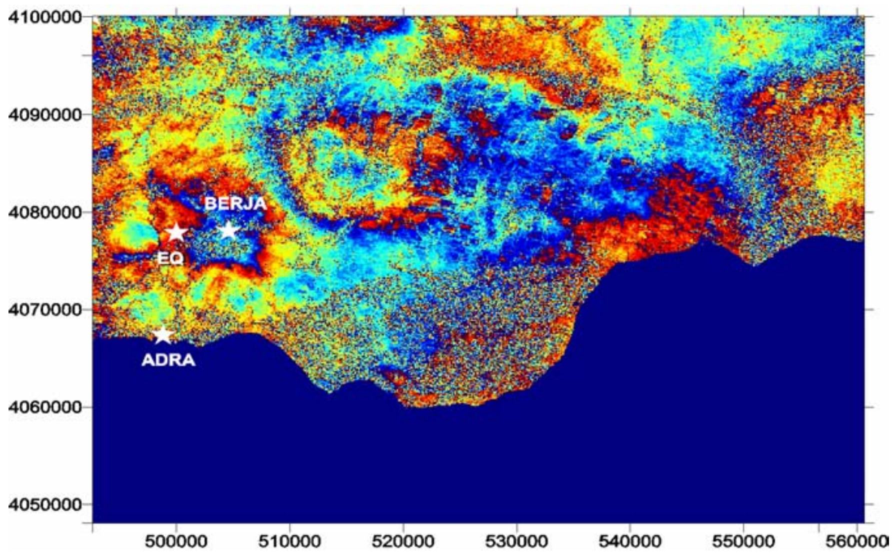

Figure 17. 18dec93-3oct95 interferogram with the location of Adra and Berja cities and Adra earthquake epicentre (EQ). Two patterns of deformation can be seen: the right one indicates an uplift and the left a subsidence.

The fault associated to this earthquake is not visible on the free surface, as occurs with most earthquakes in the south of the Iberian peninsula. This makes it difficult to conduct any detailed study because there is no data about the surface deformation. The only data available are those provided by the seismic network of the zone, and by the portable array installed after the first earthquake occurred.

To try to detect the displacements produced by this earthquake using InSAR we have used two images: one before the event, December 18, 1993 and another after the event, October 3, 1995. A Digital Elevation Model was used to remove the topography and to obtain the differential interferogram (Figure 17). Two patterns of one cycle fringe with different signs are seen. The right one indicates an uplift and the left a subsidence. This result matches the type of fault (normal: strike is 300º, dip is 80º and rake is –120º (Morales, personal communication)) and its depth (8 km) [e.g., Rundle, 1982; Fernández et al., 1996; Fernández et al., 1999). However, the location of the deformation, far from the epicentre, might show that these fringes are of atmospheric origin. Furthermore, deformation looks large for a small 8 km depth earthquake as this one (see e.g., Rigo and Massonnet, 1999).

5. SUMMARY AND CONCLUSIONS

This paper present the results obtained after applying InSAR in the Canary Islands, using radar images from 1992 to 2000. During 2000 and 2001 we began using the EPSIE2000 software for the steady-state processing of radar images in Canaries, and started assessing long-term stability coherence. This was easily achieved thanks to the volcanic nature of the archipelago. However, the authors not only assessed the feasibility of the technique, but also demonstrated that it can operationally yield results that cannot be achieved by any other means. This is the case of the deformations detected in Tenerife in areas not covered by traditional monitoring systems. These results prompted the authors to design and observe a global GPS network, with which they demonstrated that periodical observation should be included in routine geodetic monitoring to complement radar observations (Rodriguez-Velasco et al., 2002; Fernández et al., 2002a).

We have not found any displacement over 3 cm on Lanzarote and La Palma using InSAR, but consider that SAR interferometry could be combined with terrestrial techniques to improve the chances of detecting possible deformation and enhance coverage, thus permitting better interpretation.

In the second stage, the research was extended to Ecuador (Tungurahua volcano and Galapagos Islands) to test this technique in a more active volcanic area. The coherence achieved in Galapagos was excellent due to its volcanic origin, ground deformations being recorded in the four volcanoes studied (Fernandina, Cerro Azul, Sierra Negra and Alcedo). This technique has proven to be an excellent tool for monitoring volcanoes in a remote area like this. Coherence was lowest at Tungurahua, due to the abundant vegetation around the volcano and the snow on its summit, and only a small area of the volcano could be monitored. No ground deformation was detected, despite this volcano being one of the most active in Ecuador in recent years.

In seismic monitoring, deformations associated to the Adra earthquake are under consideration to assess whether or not this deformation is of atmospheric origin.

All results have proven that InSAR can be used as a monitoring technique in volcanic and seismic regions. Overall, we have tried to exploit the large advantages of InSAR to obtain ground displacements maps (with centimetric accuracy) of 100 km^2 area. Despite InSAR's drawbacks (coherence and atmospheric interferences) in some scenarios, if suitable images are selected these drawbacks can be solved and InSAR monitoring can be applied to complement ground monitoring in remote areas.

ACKNOWLEDGEMENTS

This work has been conducted under European Space Agency contract nº 13661/99/I-CD and with support from MCyT project AMB99-1015-C02. We thank CLIRSEN (Centro de Levantamiento de Sensores Remotos (CLIRSEN) and Instituto Geofísico, both of them in Ecuador, for Galapagos and Tungurahua DEM's and geological and terrestrial data in Galapagos and Tungurahua volcano.

REFERENCES

ABLAY G. J. AND KEAREY P. H. (2000): «Gravity constraints on the structure and volcanic evolution of Tenerife, Canary Islands», *J. Geophys. Res*., **105**, 5783-5796.

AMELUNG, F., GALLOWAY, D. L., BELL, J. W., ZEBKER, H. A. AND LACZNIAK, R. J. (1999): «Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation», *Geology*, **27**, 6, 483-486.

AMELUNG, F., JÓNSSON, S., ZEBKER, H. A. AND SEGALL, P. (2000): «Widespread uplift and 'trapdoor' faulting on Galápagos volcanoes observed with radar interferometry», *Nature*, **407**, 993-996.

ANCOCHEA, E., FÚSTER, J. M., IBARROLA, E., CENDRERO, A., COELLO, J., HERNÁN, F., CANTAGREL, J. M. AND JAMOND, C. (1990): «Volcanic evolution of the island of Tenerife (Canary Islands) in the light of new K-Ar data», *J. Volcanol. Geotherm. Res*., **44**, 231-249.

ARAÑA, V. (2000): «Reflexiones tras la noticia de una posible catástrofe volcánica en la isla de La Palma», *Boletín informativo de la Casa de los Volcanes*. Lanzarote. 5, 2-3.

ARAÑA, V. (editor) (1997): «Guía de Lanzarote», *Serie Casa de los Volcanes*, **6**. 128 pp.

ARAÑA, V. AND ORTIZ, R. (1991): «The Canary Islands: Tectonics, magmatism and geodynamic framework», in Kampunzu AB and Lubala RT (eds) *Magmatism in* *extensional structural settings. The Phanerozoic African Plate*. Springer-Verlag Berlin, 209-249.

ARAÑA, V., FELPETO, A., ASTÍZ, M., GARCÍA, A., ORTÍZ, R. AND ABELLA, R. (2000a): «Zonation of the main volcanic hazards (lava flows and ash fall) in Tenerife, Canary Islands. A proposal for a survillance network», *J. Volcanol. Geotherm. Res*., **103**, 377-391.

ARAÑA, V., CAMACHO, A. G., GARCÍA, A., MONTESINOS, F. G., BLANCO, I., VIEIRA, R. AND FELPETO, A. (2000b): «Internal structure of Tenerife (Canary Islandas) based on gravity, aeromagnetic and volcanological data», *J. Volcanol. Geotherm. Res*., **103**, 43-64.

ARNOSO, J., FERNÁNDEZ, J. AND VIEIRA, R. (2001): «Interpretation of tidal gravity anomalies in Lanzarote, Canary Islands», *Journal of Geodynamics*, **31**, 341-354.

AVALLONE, A., ZOLLO, A., BRIOLE, P., DELACOURT, C. AND BEAUDUCEL, P. (1999): «Subsidende of Campi Flegrei (Italy) detected by SAR interferometry», *Geophys. Res. Lett*., **26**, 15, 2303-2306.

BEAUDUCEL F., BRIOLE, P., AND FROGER, J. L. (2000): «Volcano-wide fringes in ERS syntheric aperture radar interferograms of Etna (1992-1998): Deformation or tropospheric effect? », *J. Geophys. Res*., **105**, 16391-16402.

BLANCO, M. J., CASAS, B. J. AND MORENO, M. J. (2000): «Red de vigilancia volcánica del Centro Geofísico de Canarias del Instituto Geográfico Nacional», in *Curso Internacional de Volcanología y Geofísica volcánica*, edited by M. Astiz and A. García, 341-350.

BUFORN E., SANZ DE GALDEANO, C. AND UDÍAS, A. (1995): «Seismotectonics of the Ibero-Maghrebian region», *Tectonophysics*, **248**, 247-261.

BÜRGMANN, R., ROSEN, P. A. AND FIELDING, E. J. (2000): «Synthetic Aperture Radar Interferometry to measure Earth's surface topography and its deformation», *Annu. Rev. Earth Planet. Sci*., **28**, 169-209.

CARNEC, C., MASSONNET, D. AND KING, C. (1996): «Two examples of the use of SAR interferometry on displacement-fields of small spatial extent», *Geophys. Res. Lett*., **23**, 3579-82.

CARRASCO, D., FERNÁNDEZ, J., ROMERO, R., ARAÑA, V., MARTÍNEZ, A., MORENO, V. AND PAGANINI, M. (2000): «First results from operational volcano monitoring in the Canary Islands», *Proc. ERS-ENVISAT SYMPOSIUM Looking down to Earth in the New Millennium*, Gothenburg, Sweden 16-20/10/2000. ISBN 92-9092-685-6. 6 pp.

CATURLA, J. L., (1996): *REGCAN95, Nueva Red Geodésica de las Islas Canarias*, Instituto Geográfico Nacional, Area de Geodesia. Internal Report.

CHADWICK, W. W. AND HOWARK, K. A. (1991): «The pattern of circmferential and radial eruptive fissures on the volcanoes of Fernandina and Isabela islands, Galapagos», *Bull. Volcanol*., **53**, 259-275.

DAY, S. J., CARRACEDO, J. C., GUILLOU, H. AND GRAVESTOCK, P. (1999): «Recent structural evolution of the Cumbre Vieja volcano, La Palma, Canary Islands: volcanic rift zone reconfiguration as a precursor to volcano flank instability*?*», *J. Vol. Geotherm. Res*., **94**, 135-167.

FELPETO, A., ARAÑA, V., ORTIZ, R., ASTIZ, M. AND GARCÍA, A. (2001): «Assesment and modelling of lava flow hazard on Lanzarote island (Canary Islands)», *Natural hazards*, 23, 247-257.

FERNÁNDEZ, J., VIEIRA, R., DÍEZ, J. L. AND TORO, C. (1992): «Investigations on crustal thickness, heat flow and gravity tide relationship in Lanzarote island», *Physics of the Earth and Planetary Interiors*, **74**, 199-208.

FERNÁNDEZ, J., YU, T.-T, RODRIGUEZ-VELASCO, G., GONZÁLEZ-MATESANZ, J., ROMERO, R., RODRIGUEZ, G., QUIRÓS, R., DALDA, A., APARICIO, A. AND BLANCO, M. J. (2002a): «New Geodetic Monitoring System in the Volcanic Island of Tenerife, Canaries, Spain. Combination of InSAR and GPS Techniques», in press.

FERNÁNDEZ, J., ROMERO, R., CARRASCO, D., LUZÓN, F. AND ARAÑA, V. (2002b): «InSAR Volcano and Seismic Monitoring in Spain. Results for the Period 1992-2000 and Possible Interpretations», *Optics and Lasers in Engineering*,**37**, 285-297.

FERNÁNDEZ, J., YU, T.-T. AND RUNDLE, J. B. (1996): «Deformation produced by a rectangular dipping fault in a viscoelastic-gravitational layered Earth model. Part I: Thrust fault. FLTGRV and FLRGRH FORTRAN programs», *Computers & Geosciences*, **22**, 735-750.

FERNÁNDEZ, J., YU, T.-T., AND RUNDLE, J. B., (1999): «Corrigenda to "Deformation produced by a rectangular dipping fault in a viscoelastic-gravitational layered Earth model. Part I: thrust fault. fltgrv and fltgrh FORTRAN programs», *Computers & Geosciences*, **25**, 301-307.

FIELDING, E. J., BLOM, R. G. AND GOLDSTEIN, R. M. (1998): «Rapid subsidence over oil fields measured by SAR interferometry», *Geophys. Res. Lett*., **25**, 3215-3218.

FRUNEAU, B. AND SARTI, F. (2000): «A method for the automatic characterization of interferometric fringes free of atmospheric artifacts: application to the study of the subsidences on the city of Paris», *Proceedings of the CEOS SAR Workshop 1999*, 679-685.

GALLOWAY, D. L., HUDNUT, K. W., INGEBRITSEN, S. E., PHILLIPS, S. P., PELTZER, G., ET AL. (1998): «Detection of aquifer system compaction and land subsidence using interferometric synthetic aperture radar, Antelope Valley, Mojave Desert, California», *Water Resour. Res*., **34**, 2573-85.

GOLDSTEIN, R. (1995): «Atmospheric limitations to repeat-track radar interferometry», *Geophys. Res. Lett*., **22**, 18, 2517-2520.

GOLDSTEIN, R. M., ENGELHARDT, H., KAMB, B. AND FROLICH, R. M. (1993): «Satellite radar interferometry for monitoring ice sheet motion: Application to an Antartic ice stream», *Science*, **262**, 1525-1530.

HALL, M. L., ROBIN, C., BEATE, B., MOTHES, P. AND MONZIER, M. (1999): «Tungurahua Volcano, Ecuador: structure, eruptive history and hazards», *J. Volcanol. Geotherm. Res*., **91**, 1-21.

HANSEEN, R. F. (2001): *Radar Interferometry: Data interpretation and error analysis*, Kluwer Academic Publishers, The Netherlands, 308 pp.

JÒNSSON, S., ZEBKER, H., CERVELLI, P., SEGALL, P., GARBEIL, H., MOUGINIS-MARK, P. AND ROWLAND, S. (1999): «A shallow-dipping dike fed the 1995 flank eruption at Fernandina volcano, Galápagos, observed by satellite radar interferometry», *Geo. Res. Lett*., **26**, 8, 1077-1080.

JOUGHIN, I., KWOK, R. AND FAHNESTOCK, M. (1998): «Interferometric Estimation of Three-Dimensional Ice-Flow Using Ascending and Descending Passes», *IEEE Trans. Geosci. Remote Sens*., **36**, 1, 25-37.

JOUGHIN, I., TULACZYK, S., FAHNESTOCK, M. AND KWOK, R. (1996) A minisurge on the Ryder Glacier, Greenland observed via satellite radar interferometry», *Science*, **274**, 228-230.

LANARI, R., LUNDGREN, P. AND SANSOTI, E. (1998): «Dynamic deformation of Etna volcano observed by satellite radar interferometry», *Geophys. Res. Lett*., **25**, 1541-1544.

MARTÍNEZ SOLARES, J. M. AND PASCUAL, G. (1996): «Efectos de los terremotos de Almería de 1993-94», *Avances en Geofísica y Geodesia*, **1**, 85-90.

MARTÍNEZ, A. AND MORENO, V. (1997): «EPSIE SAR Processing Environment», *Proceedings of ESA Symposium on the use of ERS data in South America,* 275-280.
MASSONET, D. AND FEIGL, K. L. (1998): «Radar Interferometry and its application to changes in the Earth's surface», *Rev. Geophys*., **36**, 441-500.
MASSONNET, D., FEIGL, K., ROSSI, M. AND ADRAGNA, F. (1994): «Radar interferometric mapping of deformation in the year after the Landers earthquake», *Nature*, **369**, 227-30.
MASSONNET, D., HOLZER, T. AND VADON, H. (1997): «Land subsidence caused by the East Mesa Geothermal Field, California, observed using SAR interferometry», *Geophys. Res. Lett*., **24**, 901-904.
MASSONNET, D., THATCHER, W. AND VADON, H. (1996): «Detection of postseismic fault-zone collapse following the Landers earthquake», *Nature*, **382**, 612-616.
MASSONNET, D. AND SIGMUNDSSON, F. (2000): «Remote Sensing of Volcano Deformation by Radar Interferometry from Various Satellites», in *Remote Sensing of Active Volcanism*, Geophysical Monograph **116**, AGU eds., 207-221.
MASSONNET, D., ROSSI, M., CARMONA, C., ADRAGNA, F., PELTZER, G., FEIGL, K. AND RABAUTE, T. (1993): «The displacement field of the Landers earthquake mapped by radar interferometry», *Nature*, **364**,138-142.
MASSONNET, D., BRIOLE, P. AND ARNAUD, A. (1995): «Deflaction of Mount Etna monitored by spaceborne radar interferometry», *Nature*, **375**, 567-570.
MICHEL, R., AVOUAC J. P. H. AND TABOURY, J. (1999): «Measuring near field coseismic displacements from SAR images: application to the Landers earthquake», *Geophys. Res. Lett*., **26**, 19, 3017-20.
MOSS, J. L., MCGUIRE, W. J. AND PAGE, D. (1999): «Ground deformation monitoring of a potential landslide at La Palma, Canary Islands», *J. Vol. Geotherm*. Res., **94**, 251-265.
OZAWA, S., MURAKAMI, M., FUJIWARA, S. AND TOBITA, M. (1997): «Synthetic aperture radar interferogram of the 1995 Kobe earthquake and its geodetic inversion», *Geophys. Res. Lett*., **24**, 18, 2327-30.
POLLITZ, F. F., PELTZER, G., AND BÜRGMANN (2000): «Mobility of continental mantle: Evidence from postseismic geodetic observations following the 1992 Landers earthquake», *J. Geophys. Res*., **105**, B4, 8035-8054.
RIGO, A. AND MASSONNET, D. (1999): «Investigating the 1996 Pyrenean earthquake (France) with SAR Interferometry heavily distorted by atmosphere», *Geophy. Res. Let*., **26**, 3217-3220.
RODRIGUEZ-VELASCO, G., ROMERO, R., YU, T.-T, GONZÁLEZ-MATESANZ, J., QUIRÓS, R., DALDA, A., APARICIO, A., CARRASCO, D. AND FERNÁNDEZ, J. (2002): «On the surface displacement monitoring in the connection with volcano reactivation in Tenerife, Canary Islands, using space techniques», *Física de la Tierra* (this volume).
ROMERO, R., FERNÁNDEZ, J., CARRASCO, D. AND ARAÑA V. (2002): «A new approach to the monitoring of deformation on Lanzarote (Canary Islands): an 8-year radar perspective», *Bull. Volcan*., DOI 10.1007/s00445-002-0232-3.
ROMERO, C. (2000): «Actividad volcánica histórica en las Islas Canarias», in Astiz M y García A (ed) *Curso internacional de Volcanología y Geofísica volcánica*. Excmo. Cabildo Insular de Lanzarote, 115-128.
RUEDA, J., MEZCUA, J. AND SÁNCHEZ RAMOS, M. (1996): «La serie sísmica de Adra (Almería) de 1993- 1994 y sus principales consecuencias sismotectónicas», *Avances en Geofísica y Geodesia*, **1**, 91-98.

RUNDLE, J. B. (1982): «Deformation, gravity and potential change due to volcanic loading of the crust», *J. Geophys. Res*., **87**, 10724-10744

SALAZAR, J. M. L., PÉREZ, N. M. AND HERNÁNDEZ, P. A. (2000): «Secular variations of soil CO2 flux levels at the summit cone of Teide volcano, Tenerife, Canary Islands», *Eos Trans*. AGU, **81**, 48, Fall Meet. Suppl., F1317.

SEVILLA, M. J. AND ROMERO, P. (1991): «Ground deformation control by statical analysis of a geodetic network in the Caldera of Teide», *J Volcanol. Geotherm. Res.*, **47**, 65-74.

SIMKIN, T. AND HOWARD, K. A. (1970): «Caldera Collapse in the Galápagos Islands, 1968», *Science*, **169**, 429-437.

SIMKIN, T., (1984): «Geology of Galapagos Islands», in R. Perry (ed), *Galapagos*. Pergamon Press, Oxford: 15-41.

TOBITA, M., FUJIWARA, S., OZAWA, S., ROSEN, P. A., FIELDING, E. J., ET AL. (1998): «Deformation of the 1995 North Sakhalin earthquake detected by JERS-1/SAR interferometry», *Earth Planets Space*, **50**, 313-325.

VIEIRA, R., TORO, C. AND ARAÑA, V. (1986): «Microgravimetric survey in the Caldera of Teide, Tenerife, Canary Islands», *Tectonophysics*, **130**, 249-257.

VIEIRA, R., VAN RUYMBEKE, M., FERNANDEZ, J., ARNOSO, J. AND TORO, C. (1991): «The Lanzarote underground laboratory», *Cahiers du Centre Européen de Géodynamique et de Séismologie*, **4**, 71-86.

WARD, S. N. AND DAY, S. (2001): «Cumbre Vieja volcano-Potential collapse and tsunami at La Palma, Canary Islands», *Geophys. Res. Lett*., **28**, 17, 3397-3400.

WILLIAMS, S., BOCK, Y. AND FANG, P. (1998): «Integrated satellite interferometry: tropospheric noise, GPS estimates and implications for interferometric synthetic aperture radar products», J. Geophys. Res., **103**, 27051-27067.

WRIGHT, T., FIELDING, E. AND PARSONS, B. (2001): «Triggered slip: observations of the 17 August 1999 Izmit (Turkey) earthquake using radar interferometry», *Geophys. Res. Lett*., **28**, 1079-1082.

YU, T.-T., FERNANDEZ, J., TSENG, C.-L., SEVILLA, M. J. AND ARAÑA, V. (2000): «Sensitivity test of the geodetic network in Las Cañadas Caldera, Tenerife, for volcano monitoring», *Journal of Volcanology and Geothermal Research*, **103**, 393-407.

ZEBKER, H. A., ROSEN, P. A., GOLDSTEIN, R. M., GABRIEL, A. AND WERNER, C. L. (1994): «On the derivation of coseismic displacement fields using differential radar interferometry –the Landers earthquake», *J. Geophys. Res*., **99**, 19617-34.

ZEBKER, H. A., ROSEN, P. A. AND HENSLEY, S. (1997): «Atmospheric effects in interferometric synthetic aperture radar surface deformation and topographic maps», *J. Geophys. Res*., **102**, 7547-7563.

ZEBKER, H. A., AMELUNG, F. AND JONSSON, S. (2000): «Remote Sensing of Volcano Surface and Internal Processes Using Radar Interferometry», in *Remote Sensing of Active Volcanism*, Geophysical Monograph **116**, AGU eds., 179-205.