

## **GEODETTIC VOLCANO MONITORING IN CANARY ISLANDS. PRESENT AND NEW PERSPECTIVES.**

**J. Fernández<sup>(1)</sup> and F. Luzón<sup>(2)</sup>**

(1) Instituto de Astronomía y Geodesia (CSIC-UCM). Fac. C. Matemáticas.  
Ciudad Universitaria, 28040-Madrid.

(2) Departamento de Física Aplicada. Universidad de Almería.  
Cañada de san Urbano s/n. 04120, Almería.

### **ABSTRACT**

Traditionally, observations of seismic, hydrologic, or fumarolic activity have proven useful in volcano monitoring. Since volcanic activity almost inevitably produces deformation and gravity changes before, during, between and after the events, geodetic techniques are now included, in the light of the IAVCEI's recommendations regarding routine monitoring. They are proving to be a powerful tool in the monitoring of volcanic activity by detecting anomalies sometimes months or weeks before the magma flow leads to earthquakes or other eruption precursors. The Canary Islands, with a population of about 1.8 million people, are located less than 100 km from the African continent. Despite being on a passive margin, they are a volcanic archipelago with a long-standing history of volcanic activity that began more than 40 m.y. ago. At least a dozen eruptions occurred on the islands of Lanzarote, Tenerife, and La Palma between 1500 and 1971. This is a typical case in which the volcanic monitoring system must be carefully designed. The system must be efficient, but must also make full use of existing facilities and have acceptable installation and running costs, in line with the current level of activity. This paper describes a proposal for the geodetic monitoring system in Canary Islands using terrestrial and space techniques.

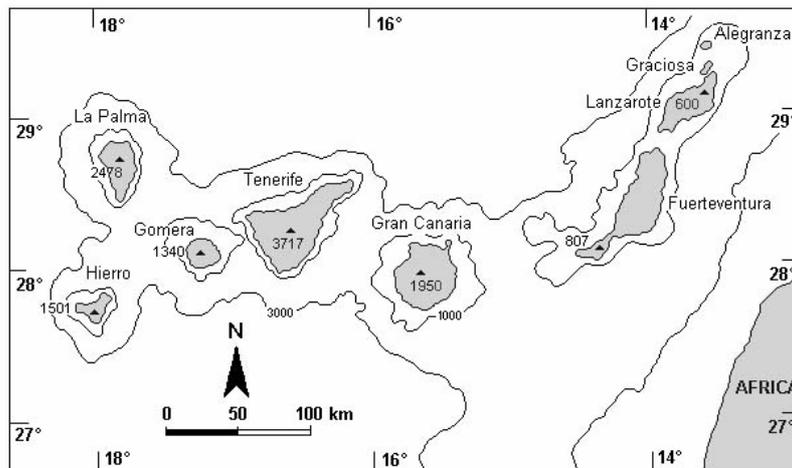
## 1. INTRODUCTION

One of the main tasks facing volcanologists studying an active volcano area is to define the most suitable instrumental monitoring system, a task that is particularly difficult in the absence of recent activity (see e.g., Fernández et al., 1999). The task not only involves the technical optimisation of the monitoring systems, but also their economic and scientific profitability. Major improvements have been made to hazard monitoring systems in recent years, but today they are still not fully reliable (Yu et al., 2000). Traditionally, observations of seismic, hydrologic, or fumarolic activity have proven useful. (see e.g. Sigurdsson et al., 2000). Other techniques that are being evaluated are those based on electromagnetic phenomena (see e.g. Araña et al, 2000). Also, in some volcanoes visual monitoring is being included via video cameras, radar or thermal image (Tárraga et al, 2001). Seismic observation involves placing a number of sensors around the volcano and sending their data to an analysis centre where they are recorded and processed (Quaas et al., 1995). Seismic monitoring can be useful for locating volcanic and tectonic sources, and for evaluating the evolution of volcanic events in time. Moreover, many approaches have tried to forecast volcanic unrest on the basis of geodetic measurement considering the widely known fact that volcanic activity causes deformations and gravity changes before, during, after and between eruptions (see e.g., Rhodes and Lockwood, 1995; Rymer and Brown, 1989; Fiske and Shepherd, 1990; Dvorak and Dzurisin, 1997; Pingue et al., 1998; Fernández et al., 1999; Sigurdsson et al., 2000; Owen et al., 2000; Yu et al., 2000; Jenzsch et al., 2001; Fernández et al., 2001a, b). Following the IAVCEI recommendations on routine monitoring, geodetic measurements are being used more and more extensively in active volcanoes and are proving capable of supplying reliable information about precursory effects. Thus geodetic monitoring complements seismic monitoring, extending the study of volcanic phenomena from seconds to years and supplying details of the development of shallow magmatic bodies (Stein et al., 2000). Therefore, given the existing diversity of geodetic techniques and the precisions attainable, nowadays they are a powerful tool in monitoring volcanic reactivation.

New space geodesy techniques such as Interferometry Synthetic Aperture Radar (InSAR) (see e.g., Massonnet and Feigl, 1998; Bürgmann et al., 2000; Hanssen, 2001) and permanent GPS observation (see e.g., Bock et al., 1997; Sagiya et al., 2000; SCIGN, 2002) have also been tested and proven to be highly useful in detecting ground displacements, and the former at a

reasonable cost. InSAR uses radar images taken by satellite, such as those supplied by the European Space Agency (ESA) ERS satellites.

Broadly speaking, the biggest volcanic eruptions are associated with polygenetic volcanoes, in other words, central volcanoes or strato-volcano with recurrent eruptions in the same volcanic structure, in which cases the region to be covered with monitoring techniques is very well defined. However, it is harder to predict future eruptions when they are not limited to a specific volcano but to a broad volcanic region (see e.g., Fernández et al., 1999). This is the situation in the Canary Islands, Figure 1, where there is an active stratovolcano, the Teide (Tenerife), and disperse monogenetic historic volcanism on different islands.



**Figure 1.** Location of the Canary Islands (Romero et al., 2003).

The Canary Islands are less than 100 km from the African continent and, despite being located on a passive margin, they are a volcanic archipelago with a long-standing history of volcanic activity that began more than 40 m.y. ago (see e.g., Araña and Ortíz, 1991). At least a dozen eruptions occurred on the islands of Lanzarote, Tenerife and La Palma between 1500 and 1971. The biggest danger of volcanic eruption that currently exists in the Canary Islands would be located in monogenetic strombolian volcanoes.

The Canary Islands are a typical case in which volcanic monitoring must be carefully designed. The system must be efficient, but at the same time must make the best possible use of all the existing facilities, with acceptable installation and running costs, according to the current level of activity on the archipelago.

This gave rise, in 1999, to two research projects, “DECIDE-VOLCANO. Promotion of space technologies for supporting the management of natural disasters: Earth observation technologies for decision support demonstration” financed by the European Space Agency, and “Seismic and volcanic risk in Spain: Study of the application of new geodetic monitoring and interpretation techniques.”, financed by the Spanish Ministry of Science and Technology (Carrasco et al., 2000a,b; Fernández et al., 2002a; Romero et al., 2002a, b). As regards volcanic risk, one of the main objectives of these projects was to design a geodetic monitoring methodology that made use of terrestrial and space techniques in the Canary Islands. Moreover, for obvious financial reasons this methodology had to make the best possible use of the infrastructure already installed on the archipelago. These research projects focused on the islands of Lanzarote, Tenerife and La Palma, which are deemed the most active islands at present. The results obtained in these projects, which will be described below, have given rise to new perspectives in the geodetic monitoring of volcanic activity on the archipelago.

### 3. PREVIOUS GEODETIC MONITORING

The National Geographical Institute (IGN) has installed a large amount of geodetic infrastructure on the Canary Islands, albeit not for monitoring purposes (Caturla, 1996; Blanco et al., 2000). This infrastructure, which is to be found on all the islands, includes a large number of geodetic vertices, high precision levelling itineraries and geodetic networks, as well as several permanent GPS observation stations in La Palma and Tenerife (Quirós, 2002; F.J. González-Matesanz, personal communication, 2002) and the permanent GPS station at Mas Palomas, in Gran Canaria, IGS station (IGS, 2002). In addition to these permanent GPS stations, the Institute of Astronomy and Geodesy has installed a GPS station at the Lanzarote Geodynamic Station (García et al., 2002; Sevilla et al., 2002).

Different gravimetric studies have also been conducted on the archipelago, mainly for structural research purposes, such as the pioneering works of the Sixties and Seventies (MacFarlane and Ridley, 1968, 1969; Dash and Bossard, 1969; Bosshard and MacFarlane, 1970; Sevilla and Parra, 1975) and those conducted at the end of the 20th century and start of the 21st (see e.g.,

Vieira et al., 1986; Camacho et al., 1988; Camacho et al., 1991; Camacho and Vieira, 1991; Camacho et al., 1996; Montesinos et al., 1999; Camacho et al., 1998; Ablay and Keary, 2000; Araña et al., 2000; Camacho et al., 2001), as well as observations of gravimetric tides (see e.g., Fernández et al., 1992, Arnosó et al., 2000).

All of this provides geodetic information, coordinates and accurate gravity values. Furthermore, different volcanic activity monitoring studies have been conducted, in particular on the islands of Tenerife, Lanzarote and La Palma, which are described briefly.

### **3.1 Tenerife**

The 17-vertices geodetic micro-network installed in Tenerife at Caldera de Las Cañadas (Sevilla and Martín, 1986; Sevilla et al., 1986; Sevilla and Romero, 1991; Sevilla and Sánchez, 1996) has been observed with traditional terrestrial methods on different occasions since 1982 to detect possible deformations associated with volcanic reactivation. It was also used as a procedure for solving configuration problems, because is located to the south of the caldera, where there are two morphologically different zones, and the vertices are located in both of them. Also connected to this network are levelling profiles (Sevilla et al., 1996) that were installed in 1994 and have been observed various times using precision trigonometric levelling. According to the observations made from 1982 to 2000 in the micro-network and the profiles, there is no displacement (Sevilla, M.J., 2002, personal communication).

Yu et al. (2000) conducted a theoretical study of this micro-network, clearly showing that it had to be extended to cover the whole island if it was to be used efficiently for monitoring purposes. See Rodríguez-Velasco et al. (2002b) for more details.

### **3.2 Lanzarote**

The structural and geodynamic characteristics of Lanzarote, and the possibility of future volcanic activity led the Institute of Astronomy and Geodesy (IAG), in collaboration with the Local Government (Cabildo Insular) to install a permanent Geodynamic Laboratory on the island in 1987 (Fernández et al. 1993; Vieira 1994). One of this Laboratory's chief objectives is to research the island's volcanic activity and the associated seismicity. The Laboratory, Figure 3, consists of four modules, three located in Cueva de los Verdes, inside the volcanic tunnel of the La Corona volcano, and the fourth in

Timanfaya National Park. Since 1987, the Laboratory has been fitted with different instruments that permit the continuous observation of deformations, gravity changes, sea level, rock temperature, etc. All the modules are connected to the Casa de los Volcanes, which sends the data via modem to the Institute in Madrid. None of the data collected by the Laboratory between 1987 and 2000 have demonstrated any clear gravity change or deformation related with volcanic activity (Fernández et al. 1992; Arnosó et al. 2001a, b).

### **3.3 La Palma**

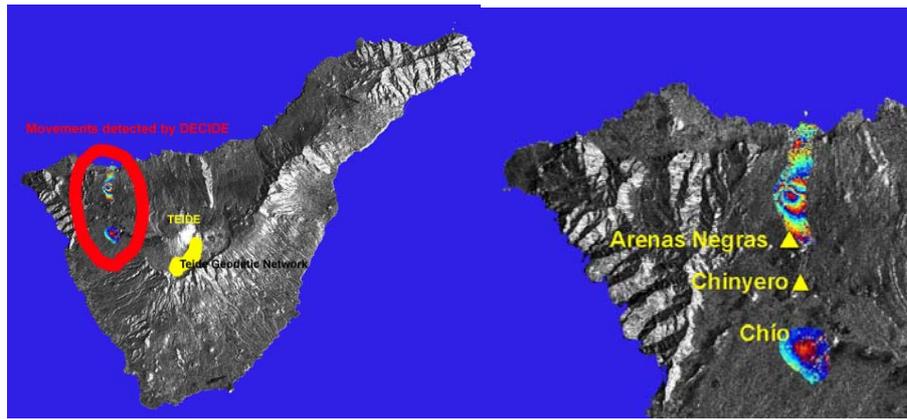
In recent years, La Palma has been one of the most closely monitored islands of the archipelago. A geodetic network was set up and observed in 1994, 1996 and 1997 with theodolite and EDM (see e.g., Moss et al., 1999). The initial 11-vertices network covered the system of faults that developed on the upper flank of Cumbre Vieja during the 1949 eruption. In 1997, the network was extended and reobserved using GPS, so as to incorporate the western flank and southern area of the island. The results obtained comparing the different campaigns are in the range of error of the techniques used.

## **4. NEW RESULTS**

The new research conducted in the context of the aforementioned projects has provided highly relevant results with regard to the monitoring of a possible volcanic reactivation in the Canary Islands. The results for each island are as follows.

### **4.1 Tenerife**

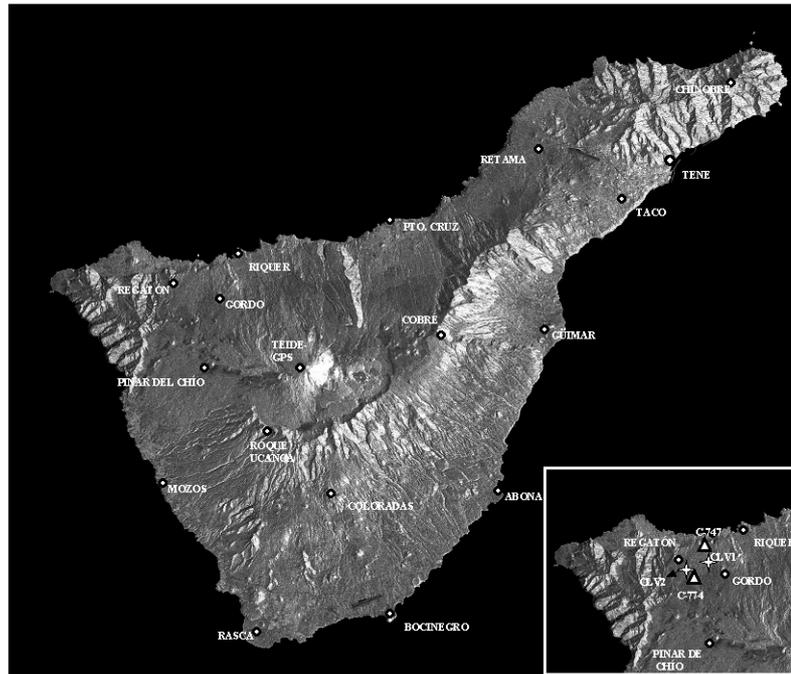
In the framework of the aforementioned projects, InSAR was applied to the island from 1999 (Carrasco et al., 2000a,b; Fernández et al., 2002a; Romero et al., 2002a). using 18 images taken by ESA satellites ERS-1 and 2, for the period from 1992 to 2000. The Las Cañadas area interferograms revealed no deformation between 1993 and 2000 equal to or in excess of one cm, matching the results obtained from the existing traditional networks. However, when this technique was used to cover the whole island, it revealed deformations in two areas, see Figure 2 (Carrasco et al., 2000b; Romero et al., 2002b).



**Figura 2-** Deformation zones detected using InSAR in Tenerife Island from 1992 to 2000. (Fernández et al., 2002a)

The first deformation is located in the Garachico zone, where an area of 15 km<sup>2</sup> in the Arenas Negras volcano lava flow sank approximately 10 cm between 1993 and 2000, while the second deformation was detected in the Pinar de Chío zone, where an area of 8 km<sup>2</sup>, located to the south of the first deformation, sank approximately 3 cm between 1993 and 2000.

These results further emphasized the need to define a GPS network covering the whole island, with several objectives: the monitoring of deformations on the island, supplementing the radar observations, and the validation of the deformations detected. Therefore a main network formed by 18 stations was designed, using geodetic vertices installed by the IGN, and with coordinates in the REGCAN95 system (Fernández et al., 2002b; Rodríguez-Velasco et al., 2002a, b), implemented by the IGN within the link between the Canary Islands and European control network EUREF. The permanent station in Santa Cruz de Tenerife was added to this network. In the area to the south of Garachico, the main network was densified for the purpose of verifying the deformations. The network, which is displayed in Figure 3, was observed in 2000 and 2001. The results (Fernández et al., 2002b, Rodríguez-Velasco et al., 2002a, b; González-Matesanz et al., 2002) validated the deformation detected in Pinar de Chío. New observation campaigns will have to be conducted in order to compare the displacements found to the south of Garachico, mainly because the observations, in particular at the fourth order points used in the densification network, were not accurate enough.



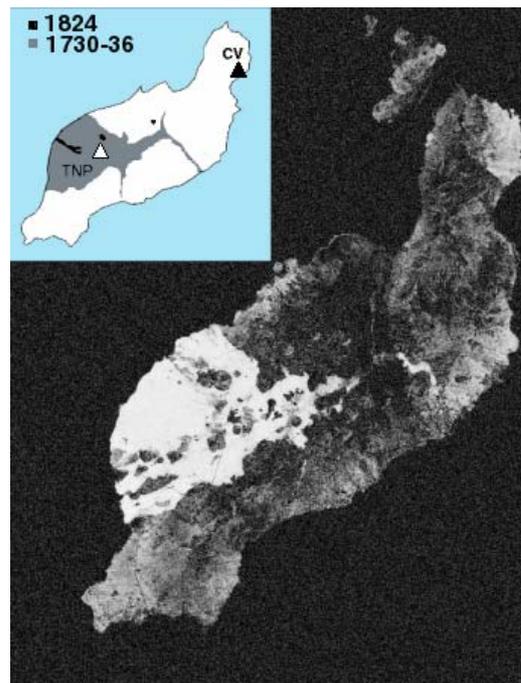
**Figura 3.** GPS network in Tenerife (Fernández and Luzón, 2002).

Vertical displacements in the form of collapses in excess of ten centimetres have also been found elsewhere on the island, such as the Retama geodetic vertex. The displacements have been found in areas where large amounts of groundwater have been drawn on the island (Government of Canary Islands and Cabildo Insular de Tenerife, 1989), so the two phenomena could be related to one another. Further research is required to ascertain whether indeed they are related, because if so, it could have major implications in the design of geodetic monitoring on the island, which should be capable of distinguishing between the different possible causes of any displacement measured on the island.

However, these new techniques have served to design a new geodetic monitoring methodology for the whole island, combining GPS and SAR observations, permitting effective detection of displacements.

#### 4.2 Lanzarote

The Island of Lanzarote was studied with InSAR techniques to detect possible deformations using images taken by the ERS satellites from 1992 to 2000 (Carrasco et al., 2000a, b; Fernández et al. 2002; Romero et al, 2002b). This study confirmed the stability of the long-term coherence due to the island's volcanic nature (Figure 4).



**Figura 4.** Coherence image obtained using two images from 12Aug95 and 16Aug97 and sketch map of Lanzarote island (upper left side of figure) showing the areas covered by the last two eruptions. The location of the different modules of the Geodynamic Laboratory are marked with CV (Cueva de los Verdes modules) and TNP (Timanfaya National Park module) (Romero et al., 2003).

This result is very important because it warrants that InSAR can be used for the systematic monitoring of the island.

The conclusion drawn after analysing the interferograms is that, during the period 1992-2000, there was no significant displacement that can be associated to volcanic reactivation on the island of Lanzarote, and this result tallies with those obtained in the Geodynamic Laboratory for the same period (Romero et al, 2002b).

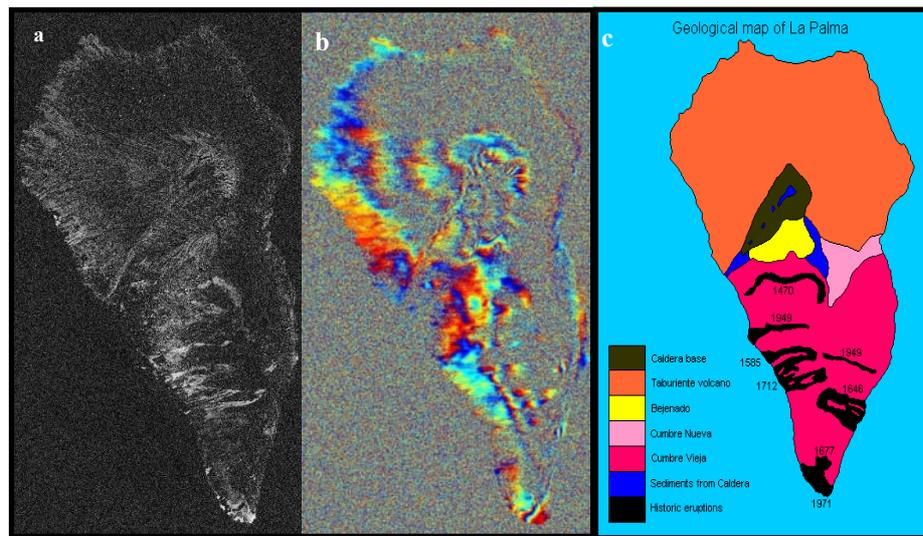
#### **4.3 La Palma**

The InSAR study of La Palma was based on 6 radar images taken by the ESA satellites ERS-1 and ERS-2 from 1992 to 1999. No digital model of the terrain was available during this first stage, so only 3 interferograms were processed with those 6 images (Fernández et al., 2002a; Romero et al., 2002a, b). The analysis revealed no instances of deformation in excess of ten centimetres, although small deformations may be masked in the uncorrected interferograms. These results are consistent with those obtained through the observation of the existing geodetic network (Moss et al., 1999).

Much of this island is covered by abundant vegetation, meaning that the coherence is not good enough. The areas of greatest coherence are in recent lava flows of the last eruptions located to the south of the island, see Figure 5. At present, a more comprehensive study is being conducted with a digital model of the terrain supplied by the IGN. See Fernández et al. (2002) and Romero et al. (2002a, b) for further details.

### **5. PROPOSED FUTURE GEODETIC MONITORING SYSTEM**

Our results clearly show that adding InSAR as a new geodetic technique for monitoring volcanic reactivation in the Canary Islands enhances the likelihood of detecting possible displacements as eruption precursors by supplying images of very large areas of the different islands. In particular, it helps to solve the problem caused by the limited spatial coverage of the geodetic observations normally made on the archipelago. A reference geodetic framework for deformation studies could be established and maintained by defining and using a network of permanent GPS stations on the Canary Islands, in combination with the IGS system, and including the Mas Palomas station. There should be at least one permanent GPS station on each island to serve as a reference station in the observation of the networks defined on each island.



**Figura 5.** (a) Coherence and (b) interferogram obtained using images of the dates October 10, 1993 and August 20, 1995 (688 days of separation). Orthogonal baseline of 12 m. (c) shows a geological map of La Palma island. The higher coherence areas correspond to lava flows of last eruptions occurred in the island. (Fernández et al., 2002a)

It is also worth noting that neither of these techniques, InSAR and GPS, is totally efficient on its own in monitoring displacement: the consistency throughout the islands is not good enough to obtain accurate InSAR results, and at present the InSAR technique cannot be used to obtain the three components of the possible displacements; furthermore, GPS observations only provide specific point measurements. However, displacements can be detected efficiently when the two techniques are combined (see e.g., Fernández et al., 2002b; Rodríguez-Velasco et al., 2002a, b).

Furthermore, theoretical and experimental studies (see e.g., Fernández et al., 2001a, b, c) have underscored the need for deformation and gravity change data to be available at the same time in order to correctly interpret the anomalies observed in volcanic environments, and also the need for the joint inversion of such data. Therefore it is obvious that gravimetric networks must be defined. Ideally, this should be done at two levels, starting with a network of regularly-observed absolute gravimetric stations, with one station per

island, and then defining a network to cover the whole of each island. If possible, the gravimetric observation should be carried out at the same GPS stations, providing accurate information about the coordinates and gravity changes at the same points, allowing on this way the study of possible gravity gradients with enough precision. Furthermore, the absolute gravity measurement stations should also be located in the same place as the permanent GPS stations.

There follows a description of the monitoring methodologies proposed for the different islands, taking into account all these results and the conclusions of both projects, the use of the facilities already installed on the islands and the lowest possible cost. They do not include the permanent GPS station network or the absolute gravity station network, which would reinforce the proposed monitoring system if they existed.

### **Island of Tenerife**

Tenerife would be monitored with the InSAR technique, using 6 images a year, this number having been chosen taking into consideration the deformations detected on the island. This technique would be supplemented with the simultaneous observation of the GPS network covering the whole island and a gravimetric network. The gravimetric network should coincide with the GPS network, permitting control of any altitude changes in the stations, which otherwise would be impossible. In periods without any clear activity, these networks would be observed every two or three years. At present, it will necessary to define network densifications in the deformation areas, similar to the one already defined that covers the areas of Pinar de Chío and to the south of Garachico, which should be observed more often, in principle once a year.

Another issue that matters on the island of Tenerife, apart monitoring volcanic reactivation, is the aforementioned need to find out whether or not there is any displacement associated to the groundwater extraction. Once it has been determined whether any such relationship exists, the methodology proposed for the island will probably have to be reconsidered.

### **Island of Lanzarote**

The Geodynamics Laboratory that already exists on this island could be used as the main tool, choosing the appropriate instruments and how to process the continuously recorded data. This would be supplemented with the InSAR, in this case only using 3 images a year, considering that no

displacement has been detected in the last ten years. It would also be necessary to define GPS and gravimetric networks similar to those defined for Tenerife, but with a longer observation period, perhaps 5 years, because the laboratory instrumentation would provide the first alarm.

### **Island of La Palma**

On this island we would use InSAR, with 6 images a year, at least in the first stage until it has been clearly established whether or not there is any displacement on the island. This technique would be combined again with the observation of a GPS network covering the whole island and of a gravimetric network of similar characteristics to the previous ones. In principle, the observation frequency would be the same as on Tenerife. Once it has been determined whether or not there is any displacement on the surface of the island, the network observation frequency and number of satellite radar images per year would have to be redefined.

### **Other Islands**

On the other Islands, and unless clear anomalies are detected, in principle we intend to use InSAR with 2 to 3 images a year, and to define gravimetric and GPS networks. In principle, these networks would be observed for approximately 5 years, unless any anomaly was detected by using InSAR or other monitoring techniques. Therefore a databank could be built for future scientist and monitoring purposes.

## **6. SUMMARY AND CONCLUSIONS**

To define the most suitable volcano monitoring system is a particularly difficult task in the absence of recent activity. It must take into account not only the technical optimisation of the monitoring systems, but also their economic and scientific profitability. Nowadays, and following the IAVCEI's recommendations regarding routine monitoring geodetic techniques must be included in this monitoring system. Those techniques complements others, such as seismic monitoring, by extending the study of volcanic phenomena from seconds to years and providing details on the growth of magma bodies within the volcano.

At least a dozen eruptions occurred in Canary Islands, on the islands of Lanzarote, Tenerife, and La Palma, between 1500 and 1971. This fact and the present activity makes it a typical case in which the volcanic monitoring

system must be carefully designed. In this paper we have described a proposal for the geodetic monitoring system in Canary Islands. This monitoring system has been developed on the basis of experimental results from different research projects and the application of theoretical analysis. This system uses terrestrial and space geodetic techniques (GPS, InSAR, gravimetry), and the existing geodetic infrastructure on the island installed either by the IGN or scientific establishments.

Although this proposal is based on work carried out since the Eighties and the results obtained, it is not definitive and must be revised in line with any new results and information that are obtained or become available in the future.

### ACKNOWLEDGEMENTS

This research has been funded through the Ministry of Science and Technology project AMB99-1015-C02, ESA-ESRIN Contract No.13661/99/I-DC and the MEDSAR contract with INDRA Espacio S.A.. In particular, we would like to thank all the scientific and technical staff who have participated in the research projects and the National Geographical Institute for its invaluable support and very especially to F.J. Gonzalez-Matesanz.

### REFERENCES

- ABLAY, G., AND KEAREY, P. (2000): «Gravity constraints on the structure and volcanic evolution of Tenerife, Canary Islands», *J. Geophys. Res.*, **105**, 5783-5796.
- ARAÑA, V., CAMACHO, A. G., GARCÍA, A., MONTESINOS, F. G., BLANCO, I., VIEIRA, R. AND FELPETO, A. (2000): «Internal structure of Tenerife (Canary Islands) based on gravity, aeromagnetic and volcanological data», *Journal of Volcanology and Geothermal Research*, **103**, 43-64
- ARAÑA, V. AND ORTIZ, R. (1991): «The Canary Islands: Tectonics, magmatism and geodynamic framework», in *Magmatism in extensional structural settings. The Phanerozoic African Plate*, A. B. Kampunzu, R. T. Lubala, (Eds.), pp. 209-249, Springer-Verlag, Berlin.
- ARNOSO, J., FERNÁNDEZ, J., VIEIRA, R., VÉLEZ, E. J. AND VENEDIKOV, A. P. (2000): «Results of tidal observations in Tenerife, Canary Islands», *Mar. Terr. Bull. Inf.*, **132**, 10283-10290.
- ARNOSO, J., FERNÁNDEZ, J. AND VIEIRA, R. (2001a): «Interpretation of tidal gravity anomalies in Lanzarote, Canary Islands», *Journal of Geodynamics*, **31**, 341-54
- ARNOSO, J., VIEIRA, R., VÉLEZ, E., WEIXIN, C., SHILING, T., JUN, J. AND VENEDIKOV, A. P. (2001b): «Monitoring tidal and non-tidal tilt variations in Lanzarote island (Spain)», *J Geod Soc Japan*, **47**, 456-62
- 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*, ed by M.Astiz and A.García, 341-350.

- BOCK, Y., WADOWINSKI, S., FANG, P., ZHANG, J., WILLIAMS, S., JOHNSON, H., BEHR, J., GENRICH, J., DEAN, J., DOMSELAAR, M., AGNEW, D., WYATT, F., STARK, K., ORAL, B., HUDNUT, K., KING, R., HERRING, T., DINARDO, S., YOUNG, W., JACKSON, D. AND GURTNER, W. (1997): «Southern California permanent GPS geodetic array: continuous measurements of regional crustal deformation between the 1992 Landers and 1994 Northridge earthquakes», *J. Geophys. Res.*, 18013-18033.
- BÜRGMANN, R., ROSEN, P. A. AND FIELDING, E. J. (2000): «Synthetic Aperture Radar Interferometry to measure Earth's Surface Topography and its Deformation», *Ann. Rev. Earth Planet. Sci.*, **28**, 169-209.
- BOSSHARD, E. AND MACFARLANE, D. J. (1970): «Crustal structure of the Western Canary Islands from seismic refraction and gravity data», *J. Geophys. Res.*, **75**, 4901-4918.
- CAMACHO, A. G., TORO C. AND FERNÁNDEZ, J. (1988): «Cálculo de la corrección topográfica a las observaciones gravimétricas en la Caldera del Teide obtenidas a partir del modelo topográfico digital de la isla de Tenerife», *Revista del Inst. Astron. Geod.*, **162**, 19-25.
- CAMACHO, A. G. AND VIEIRA, R. (1991): «Gravimetric study of Lanzarote island», *Cahiers Centre Eur. Geodyn. Seismol.*, **4**, 339-351.
- CAMACHO, A. G., VIEIRA, R. AND DE TORO, C. (1991): «Microgravimetric model of the Las Cañadas caldera (Tenerife)», *J. Volcanol. Geotherm. Res.*, **47**, 75-88.
- CAMACHO, A. G., MONTESINOS, F. G. AND VIEIRA, R. (1996): «Gravimetric structure of Teide volcano environment», *Proceedings of the Second Workshop on European Laboratory Volcanoes*, Thira, Santorini Island, Greece, 605-613.
- CAMACHO, A. G., MONTESINOS, F. G. AND VIEIRA, R. (1998): «Gravimetric structure of the Teide volcano environment», *The European Laboratory Volcanoes*. Volcanic Risk. European Communities. (Ed. R. Casale et al. European Commission. Science Research Development), 605-613.
- CAMACHO, A. G., MONTESINOS, F. G., VIEIRA, R. AND ARNOSO, J. (2001): «Modelling of crustal anomalies for Lanzarote (Canary Islands) in light of gravity», *Geophysical Journal International*, **147**, 95-101.
- CARRASCO, D., FERNÁNDEZ, J., ROMERO, R., ARAÑA, V., MARTÍNEZ, A., MORENO, V. AND PAGANINI, M. (2000a): «First results from operational volcano monitoring in the Canary Islands», *Proc. ERS-ENVISAT Symposium*.
- CARRASCO, D., FERNANDEZ, J., ROMERO, R., ARAÑA, V., MARTINEZ, A., MORENO, V., APARICIO, A. AND PAGANINI, M. (2000b) «First results from operational volcano monitoring in the Canary Islands» *ESA, SP-461, ERS-ENVISAT SYMPOSIUM*, Gothenburg, Sweden 16-20/10/2000. 6 pp.
- CATURLA, J. L. (1996): *REGCAN95, Nueva Red Geodésica de las Islas Canarias*, Instituto Geográfico Nacional, Area de Geodesia. Internal Report.
- DASH, B. P. AND BOSSARD, E. (1969): «Seismic and gravity investigations around the Western Canary Islands», *Earth Planet. Sci. Lett.* **7**, 169-177.
- DVORAK, J. J. AND DZURISIN, D. (1997): «Volcano geodesy: the search for magma reservoirs and the formation of eruptive vents», *Rev. of Geophys.*, **35**, 343-384.
- 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., ARNOSO, J. AND VIEIRA, R. (1993): «Investigación en riesgo volcánico en Lanzarote», *Revista de la Real Academia de Ciencias Exactas, Físicas y Naturales de Madrid*, Tomo LXXXVIII, Cuad. 2º y 3º, 479-84.

- FERNÁNDEZ, J., CARRASCO, J. M., RUNDLE, J. B. AND ARAÑA, V. (1999): «Geodetic methods for detecting volcanic unrest: A theoretical approach», *Bull. Volcanol.*, **60**, 534-544.
- FERNANDEZ, J., CHARCO, M., TIAMPO, K. F., JENTZSCH, G. AND RUNDLE, J. B. (2001a): «Joint interpretation of displacements and gravity changes in volcanic areas. A test example: Long Valley Caldera, California», *Geophysical Research Letters*, **28**, 1063-1066.
- FERNANDEZ, J., TIAMPO, K. F., JENTZSCH, G., CHARCO, M. AND RUNDLE, J. B. (2001b): «Inflation or deflation? New results for Mayon volcano applying elastic-gravitational modeling», *Geophysical Research Letters*, **28**, 2349-2352.
- FERNÁNDEZ, J., TIAMPO K. F. AND RUNDLE, J. B. (2001c): «Viscoelastic displacement and gravity changes due to point magmatic intrusions in a gravitational layered solid Earth», *Geophysical Journal International*, **146**/1, 155-170.
- FERNÁNDEZ, J., ROMERO, R., CARRASCO, D., LUZÓN, F. AND ARAÑA, V. (2002a): «InSAR Volcano and Seismic Monitoring in Spain. Results for the Period 1992-2000 and Possible Interpretations», *Optics and Lasers in Engineering*, **37**/2-3, 285-297.
- FERNÁNDEZ, J., YU, T.-T., RODRÍGUEZ-VELASCO, G., GONZÁLEZ-MATESANZ, J., ROMERO, R., RODRÍGUEZ, G., QUIRÓS, R., DALDA, A., APARICIO, A. AND BLANCO, M. J. (2002b): «New Geodetic Monitoring System in the Volcanic Island of Tenerife, Canaries, Spain. Combination of InSAR and GPS Techniques», *J. Volcanol. Geotherm. Research*, in press.
- FISKE, R. S. AND SHEPHERD, J. B. (1990): «Twelve years of ground-tilt measurements on the Soufrière of St. Vicent 1977-1989», *Bull. Volcanol.*, **52**, 227-241.
- GARCÍA, L., CANO, M. A., ORTÍZ, E. AND SEVILLA, M. J. (2002): «Determinación de coordenadas provisionales de la estación GPS permanente de Lanzarote», *Comunicaciones de la 3ª Asamblea Hispano-Portuguesa*, 4 p. (En prensa)
- GOBIERNO DE CANARIAS, CABILDO INSULAR DE TENERIFE (1989): *Plan hidrológico Insular de Tenerife. Avance: bases para el planeamiento hidrogeológico*, ed. Cab. Insul. de Tenerife, 133 pp.
- GONZÁLEZ-MATESANZ, F. J., FERNÁNDEZ, J., PRIETO, J. F., STALLER, A., RODRÍGUEZ-VELASCO, G. AND ALONSO-MEDINA, A. (2002): «Vigilancia GPS en la isla de Tenerife: metodología y resultados», *Comunicaciones de la 3ª Asamblea Hispano-Portuguesa*, 4 p. (En prensa).
- HANSSSEN, R. F. (2001): *Radar Interferometry. Data interpretation and error analysis*, Kluwer Academic publ., 308 pp.
- HERNÁNDEZ, P., PÉREZ, N., SALAZAR, J., SATO, M., NOTSU, K. AND WAKITA, H. (2000): «Soil gas CO<sub>2</sub>, CH<sub>4</sub>, and H<sub>2</sub> distribution in and around Las Cañadas caldera, Tenerife, Canary Islands, Spain», *Journal of Volcanology and Geothermal Research*, **103**, 425-438
- IGS (2002): «<http://igsb.jpl.nasa.gov/>».
- JENTZSCH, G., PUNONGBAYAN, R. S., SCHREIBER, U., SEEBER, G., VÖLKSEN, C. AND WEISE, A. (2000): «Mayon Volcano, Philippines: change of monitoring strategy after microgravity and GPS measurements», *J. Volcanol. Geotherm. Res.*, **109**, 219-234.
- MACFARLANE, D. J. AND RIDLEY, W. I. (1968): «An interpretation of gravity data for Tenerife, Canary Islands», *Earth Planet. Sci. Lett.*, **4**, 481-486.
- MACFARLANE, D. J. AND RIDLEY, W. I. (1969): «An interpretation of gravity data for Lanzarote, Canary Islands», *Earth Planet. Sci. Lett.*, **6**, 431-436.
- MASSONNET, D. AND FEIGL, K. (1998): «Radar interferometry and its application to changes in the Earth's surface», *Reviews of Geophysics*, **36**, 441-500.

- MONTESINOS, F., CAMACHO, A. G., VIEIRA, R., ARNOSO, J. AND GIL, E. (1999): «Estudio gravimétrico en la Isla de Fuerteventura (I. Canarias)», *I Asamblea Hispano-Portuguesa de Geodesia y Geofísica*, (Cd-Rom), 6 pp.
- MOSS, J. L., MCGUIRE W. J. AND PAGE, D. (1999): «Ground deformation of a potential landslide at La Palma, Canary Islands», *J. Volcanol. Geother. Res.*, **94**, 251-265.
- OWEN, S. P., SEGALL, P., LISOWSKI, M., MIKLIUS, A., DENLINGER, R. AND SAKO, M. (2000): «The rapid deformation of Kilauea volcano: GPS measurements between 1990 and 1996», *J. Geophys. Res.*, **105**, 18983-18998.
- PINGUE, F., TROISE, C., DE LUCA, G., GRASSI, V. AND SCARPA, R. (1998): «Geodetic monitoring of Mt. Vesuvius volcano, Italy, based on EDM and GPS surveys», *J. Volcanol. Geotherm. Res.*, **82**, 151-160.
- QUAAS, R., GONZÁLEZ, R., GUEVARA, E., RAMOS, E. AND DE LA CRUZ-REYNA, S. (1995): «Monitoreo Volcánico: Instrumentación y Métodos de Vigilancia», in O. Zepeda and T. A. Sánchez (eds), *Volcán Popocatepetl*, 25-76, CENAPRED, México.
- QUIRÓS, R., CANO, M., SÁNCHEZ, J., VALDÉS-PÉREZ, M., GONZÁLEZ-MATESANZ, J. AND PRIETO, J. (2002): «Estado y desarrollo de la red de estaciones de referencia GPS de España y del proyecto RECORD», *Comunicaciones de la 3ª Asamblea Hispano-Portuguesa*, 4 p. (In press)
- RHODES, J. M., AND LOCKWOOD, J. P. (Eds.) (1995): *Mauna Loa Revealed. Structure, Composition, History, and Hazards*, AGU, Washington.
- RODRÍGUEZ-VELASCO, G., ROMERO, R., YU, T.-T., GONZÁLEZ-MATESANZ, F. J., QUIRÓS, R., DALDA, A., CARRASCO, D. AND FERNÁNDEZ, J. (2002a): «Introducción de técnicas espaciales a los sistemas de vigilancia geodésica en Tenerife (Islas Canarias)», *Comunicaciones de la 3ª Asamblea Hispano-Portuguesa*, 4 p. (In press)
- RODRÍGUEZ-VELASCO, G., ROMERO, R., YU, T.-T., GONZÁLEZ-MATESANZ, F. J., QUIRÓS, R., DALDA, A., APARICIO, A., CARRASCO, D. AND FERNÁNDEZ, J. (2002b): «On the monitoring of surface displacement in connection with volcano reactivation in Tenerife, Canary Islands, using space techniques», *Física de la Tierra*, **14**, this issue.
- ROMERO, R., CARRASCO, D., FERNÁNDEZ, J., MARTÍNEZ, A., MORENO, V. AND ARAÑA, V. (2002a): «Results from DECIDE-VOLCANO Project. Application in the Canary Islands and Ecuador», *Comunicaciones de la 3ª Asamblea Hispano-Portuguesa*, 4 p. (In press)
- ROMERO, R., FERNÁNDEZ, J., CARRASCO, D., LUZÓN, F., MARTÍNEZ, A., RODRÍGUEZ-VELASCO, G., MORENO, V., ARAÑA, V. AND APARICIO, A. (2002b): «Synthetic Aperture Radar Interferometry (InSAR): Application to ground deformations studies for volcano and seismic monitoring», *Física de la Tierra*, **14**, this issue.
- ROMERO, R., CARRASCO, D., ARAÑA, V. AND FERNÁNDEZ, J. (2003): «A new approach to the monitoring of deformation on Lanzarote (Canary Islands): an 8-year radar perspective», *Bulletin of Volcanology*, **65**, 1-7. DOI 10.1007/s00445-002-0232-3.
- RYMER, H. AND BROWN, G. (1989): «Gravity changes as a precursor to volcanic eruption at Poas volcano, Costa Rica», *Nature*, **342**, 902-905.
- SAGIYA, T., MIYAZAKI, S. AND TADA, T. (2000): «Continuous GPS array and present-day crustal deformation of Japan», *Pure appl. Geophys.*, **157**, 2303-2322.
- SCIGN (2002): «<http://www.scign.org>».
- SEVILLA, M. J. AND MARTIN, M. D. (1986): «Geodetic network design for crustal deformation studies in the Caldera of Teide area», *Tectonophysics*, **130**, 235-248.

- SEVILLA, M. J., MARTÍN, M. D. AND CAMACHO, A. G. (1986): «Data analysis and adjustment of the first geodetic surveys in the Caldera of Teide, Tenerife, Canary Islands», *Tectonophysics*, **130**, 213-234.
- 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.
- SEVILLA, M. J. AND SÁNCHEZ, F. J. (1996): «Geodetic network for deformation monitoring in the Caldera of Teide», in *The European Laboratory Volcanoes*. Proc. 2<sup>nd</sup> workshop, Santorini, Greece, 2-4 May, 1996. European Commission. 615-636.
- SEVILLA, M. J., VALBUENA, J. L., RODRÍGUEZ-DÍAZ, G. AND VARA, M. D. (1996): «Trabajos altimétricos en la Caldera del Teide», *Física de la Tierra*, **8**, 117-130.
- SEVILLA, M. J., GARCÍA, L. AND ORTÍZ, E. (2002): «Red de apoyo de la estación GPS permanente de Lanzarote», *Comunicaciones de la 3ª Asamblea Hispano-Portuguesa*, 4 p. (In press)
- SIGURDSSON, H., HOUGHTON, B., MCNUTT, S. R., RYMER, H. AND STIX, J. (Eds.) (2000): *Encyclopedia of Volcanoes*, Academic Press, San Diego.
- STEIN, S., LANE, M., HAMBURGER, M., MEETERS, C., DIXON, T. AND OWEN, S. (2000): «UNAVCO Conference Explores Advance», in *Volcanic Geodesy*. EOS Trans. AGU, 81, 121-126.
- TÁRRAGA, M., GARCÍA, A., ORTIZ, R., ABELLA, R. AND PEÑA, J. (2001): «SANARIS Project: A Satellite Network for Natural Risk Monitoring», *Natural Hazards* 23, 417-429.
- VIEIRA, R. (1994): «La estación geodinámica de Lanzarote», in *Serie Casa de los Volcanes*, Cabildo Insular de Lanzarote, **3**, 31-40
- VIEIRA, R., TORO, C. AND ARAÑA, V. (1986): «Microgravimetric survey in the caldera of Teide, Tenerife, Canary Islands», *Tectonophysics*, **130**, 249-257.
- 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.